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Assessment of the Environmental and Economic Impacts of the Ban on Imports of PCBs

Versar, Inc, Springfield, Va

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ASSESSMENT OF THE ENVIRONMENTAL AND ECONOMIC IMPACTS OF THE BAN ON IMPORTS OF PCBs

JULY 1977

U.S. ENVIRONMENTAL PROTECTION AGENCY
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This report summarizes an investigation into the uses of imported polychlorinated biphenyls (PCBs) in the United States. Imported PCBs are presently used only for the maintenance of certain mining machinery. In addition, PCBs are present as a significant impurity in polychlorinated terphenyls (PCTs) imported for use in investment casting waxes. Importation of PCBs for these uses will be banned after 1977 by the Toxic Substances Control Act, unless exemptions are allowed in accordance with the provisions of the Act. The recent Directive of the Council of the European Communities (EEC) prohibits use of PCBs and PCTs in investment casting waxes, but allows continued use of PCBs in mining machinery in Europe.

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FINAL TASK REPORT

Submitted to:

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Office of Toxic Substances
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Washington, D.C.

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Submitted by:

VERSAR INC.
6621 Electronic Drive
Springfield, Virginia 22151

July 8, 1977

1a/

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PREFACE

This report summarizes an investigation into the uses of imported polychlorinated biphenyls (PCBs) in the United States. Imported PCBs are presently used only for the maintenance of certain mining machinery. In addition, PCBs are present as a significant impurity in polychlorinated terphenyls (PCTs) imported for use in investment casting waxes. Importation of PCBs for these uses will be banned after 1977 by the Toxic Substances Control Act, unless exemptions are allowed in accordance with the provisions of the Act. Recent PCB-related directives of the European Economic Community and the Organization for Economic Co-Operation and Development, plus legislation in Canada, permit at least temporarily the continued use of PCBs in mining applications but prohibit (or at least discourage) their use in tooling compounds and investment casting waxes.

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1.0 INTRODUCTION

In April of 1971, the Monsanto Company voluntarily ceased production of polychlorinated biphenyls (PCBs) destined for open-system uses - that is, those uses where losses of PCBs to the environment can not be readily controlled. The main uses for which Monsanto continues to produce PCBs are electrical capacitors and transformers, closed systems where the PCBs are used as fire resistant dielectric fluids and coolant fluids respectively. In these closed circuit applications, the PCBs are completely contained and do not normally leak into the environment during use of the equipment. It is therefore feasible to recover the PCBs at the termination of the service life. Recovery of PCBs is not feasible in such applications as carbonless copy paper, plasticizers, pesticide extenders, hydraulic fluids, adhesives, inks, and lubricants. Thus, as of 1971, users of PCBs in open-system applications have relied on imported PCBs. It is the purpose of this report to examine the current uses of imported PCBs and the current economic dependence on imported PCBs, and to recommend steps to control the imports of PCBs and the consequent losses of this toxic chemical to the U.S. environment.

Related to the problem of polychlorinated biphenyls is that of polychlorinated terphenyls (PCTs), some batches of which have been found to contain over 0.5 percent PCBs as a by-product of their manufacture. PCTs, since they are closely related chemically to PCBs, may also be an environmental hazard in their own right. In April of 1972, Monsanto ceased production of PCTs for all applications, and users were forced to import PCTs. Tivian Laboratories of Providence, Rhode Island, is the only U.S. distributor of PCTs. For the past several years, Tivian Laboratories has been certifying that the PCTs which they have sold to M. Argueso & Co., have contained less than 0.05% PCBs. Thus, in total, this report examines the uses of and current economic dependence upon imported PCBs and PCTs.

1.1 Uses of Imported PCBs and PCTs

There is only one current use of imported PCBs: Pyralene 3010, a French PCB compound, is used by the Joy Manufacturing Company of Pittsburgh as a non-flammable cooling fluid in mining machinery. Sections 2.0 and 3.0 list the volumes of PCBs imported during the years 1972 through 1976. Imports of Pyralene increased by a factor of nearly three in 1976 over the previous year.

Polychlorinated terphenyls are used in investment casting waxes and in tooling compounds. The latter application accounts for only 2 to 3 percent of the terphenyl imported for use in investment casting waxes. Of the eleven domestic investment casting wax producers, at least six have produced terphenyl waxes, and three manufacturers are currently using PCTs in their wax formulations.

Since the bulk of the imported polychlorinated polycyclic compounds are used in investment casting waxes, the investment casting industry and the wax manufacturing industry are the central topics of this report. Data on mining machinery coolants and tooling compounds are scant; Sections 3.0 and 4.0 respectively summarize current information on these applications.

1.1.1. Coolants for Mining Machinery

Among the advantages of polychlorinated biphenyls in industrial applications is their inertness and nonflammability. These properties make PCBs useful as heat transfer fluids in high temperature applications, the most well-known application being as a coolant for large electrical transformers. Electrical transformers, however, are not included in this report because Monsanto still produces PCB fluids for closed applications where there is a high probability the material will eventually be recovered and properly destroyed. With regard to mining machinery, though, PCB fluids offer many of the same advantages they offer in transformers; low combustion hazard in the event of a leak from or into a high temperature environment, very low electrical conductivity, and inertness that minimizes system corrosion even at continuous high operating temperatures.

Monsanto will cease producing all PCB formulations by the end of 1977. Transformer manufacturers are in the process of finding cost-effective alternative materials that provide adequate service. The fluid used in place of PCBs will have to be nonflammable, inert at high temperatures, noncorrosive to the containing system, and reasonable in price. Section 3.0 shows import trends for PCB mining machinery coolant for the period 1972 through 1976.

1.1.2 Tooling Compounds

Tooling compounds are wax-like materials used to fill thin-walled structures made of metal, plastic, glass or other materials so that machining can be performed without bending or buckling or otherwise damaging the structure. Aluminum or steel honeycomb structure of the kind used widely in aerospace applications is a prime example of the type of material in which tooling compounds are used. Unless the honeycomb cells are filled with some easily removable but otherwise rigid material during cutting or machining operations, the cell walls can be easily damaged. Such damage to the cell walls will reduce the strength and rigidity of the finished panel.

The properties of tooling compounds are similar to those of investment casting waxes: they must remain hard at temperatures close to the melting temperature of the wax because machining operations cause localized heating, and they should undergo minimal shrinkage during solidification and cooling. PCTs are used in tooling compounds to provide all of these properties. PCT-type tooling compounds contain 8 and 40 percent PCTs by weight. Alternatives to PCTs will have to provide approximately these same properties. Section 4.0 summarizes information taken from patents and from conversations with the single PCT tooling-compound manufacturer.

1.1.3 Investment Casting Waxes

There are eleven domestic manufacturers of investment casting wax, and there are about 150 investment casting foundries. Of the investment casting wax manufacturers, only three currently produce PCT waxes for those foundries that use PCT waxes. Of the remaining wax manufactures, one of the major ones voluntarily ceased production of waxes containing chlorinated and nitrogenous components in the early part of 1975; another stopped production of terphenyl waxes when Monsanto stopped producing PCT in 1972; and a third producer stopped manufacturing terphenyl waxes sometime within the last seven years.

Section 5.0 characterizes the technique of investment casting and the investment casting industry. Section 6.0 deals specifically with investment casting waxes. Both these sections discuss the use of PCB filler material (decachlorobiphenyl) which was used in one manufacturer's wax formulation until the middle of

1976 when the passage of state legislation banning the use of all PCBs forced termination of the manufacture of PCB-containing waxes. Import data shown in Sections 2.0, 5.0 and 6.0 indicate an increase in the imports of PCTs.

1.2 Import Volume 1972 through 1976

Data from U.S. Customs on the imports of PCBs and PCTs are summarized below. Domestic production of PCBs was terminated for most applications in April 1971; terphenyl production was terminated the following year. Hence, PCB and PCT imports began in earnest in 1972 and 1973 respectively. Shown in the table are imports of PCTs and decachlorobiphenyl (both used in investment casting waxes) and of other PCB formulations:

Year	PCTs (lbs)	Decachlorobiphenyl (lbs)	Other PCBs (lbs)
1972	0	3,547	394,912
1973	163,101	109,060	36,420
1974	290,866	0	50,795
1975	273,375	149,914	48,501
1976	275,576	0	113,581

In 1976, all the PCBs imported were from France and the port of entry, according to Customs, was Pittsburgh, indicating that all of the PCB was destined for use in mining machinery produced by the Joy Manufacturing Company. While it is apparent from the above tabulation that PCB imports decreased significantly between 1975 and 1976, two things should be noted: (1) the 1976 imports are more than twice those of 1974, and (2) the volume of PCBs destined for Pittsburgh in 1976 are nearly three times the amount in 1975. (See Sections 2.0 and 3.0.)

Terphenyl imports increased to a maximum in 1974 and have held nearly constant since. The bulk of imported terphenyls are used in investment casting waxes, and the rest is used in tooling compounds.

1.3 Summary of Present Situation

At the present time there are only four manufacturers who use imported polychlorinated polycyclic materials; one of them is the sole user of imported PCBs for use in mining machinery; two of them use terphenyls in investment casting waxes; and one uses terphenyls in investment casting waxes and tooling compounds.

There are, however, about 150 domestic investment casting foundries. Not all of these foundries use PCT-containing waxes, but among those that do, the feeling may prevail that PCT waxes offer the best properties for the particular foundry's operations and types of objects being cast. Such a feeling may be without foundation though, since there is ample evidence that precision investment casting foundries can convert over to and rely entirely upon non-PCT waxes. The General Electric foundry in Albuquerque, New Mexico, is an example; their primary product is blades for gas turbine engines, parts which are very sensitive to deviations from optimum surface finish and dimensional tolerances.

In early 1975, one wax manufacturer, the Freeman Manufacturing Company of Cleveland, Ohio, voluntarily terminated production of waxes containing either PCTs or nitrogenous components. While this company underwent some economic impact as a result of their decision, suitable substitutes for PCTs were eventually found, and Freeman has retained its position among the largest wax manufacturers.

1.4 Conclusions and Recommendations

Imported polychlorinated biphenyls are currently used by only one manufacturer in the U.S. The specific PCB formulation is called Pyralene 3010 and it is imported from France. It is used as a cooling fluid for mining machinery motors.

Imported terphenyls are used by three manufacturers of investment casting waxes; one of the manufacturers also produces a line of terphenyl-containing tooling compounds. The volume of terphenyl used in tooling compounds is on the order of only several percent of the terphenyl consumed in casting waxes; and terphenyl casting waxes account for less than half the wax sales of at least two of the three terphenyl casting wax producers.

Although one wax manufacturer has stated that there are no adequate substitutes for polychlorinated terphenyl in waxes, at least three of the eleven wax manufacturers in this country have terminated terphenyl wax production within the last eight years. One of these companies voluntarily terminated production of terphenyl waxes in early 1975; and though this company did not economically benefit by its decision, it is still very competitive and claims to have found alternatives to PCTs that perform almost if not just as well as terphenyls in most applications.

With regard to the 150 or so investment casting foundries, at least one has instituted a policy of using no casting waxes containing either PCBs or PCTs. This foundry produces turbine blades for gas turbine engines, engines that are used in commercial and military aircraft that are used throughout the world. That such parts as turbine engine components - which must operate with the highest reliability under conditions of extreme thermal and mechanical stress - can be investment cast using wax patterns that do not contain PCTs makes one wonder what exactly is meant by the phrase "there are no adequate substitutes for PCTs in investment casting waxes." This turbine-blade foundry is currently conducting a detailed study of the economic and process effects of its decision against PCB and PCT waxes.

The problem of how to control the use of imported PCBs has to an extent been obviated by the implementation of the Toxic Substances Control Act, which sets definite time limits on PCB importation. PCBs are currently imported for the single purpose of maintenance of mining machinery that uses PCB fluids as coolants for the electric drive motors. Depending upon the interpretation of the act, PCB-containing machines may have to be put out of service at the end of 1977 unless either (1) the machinery is modified to dry-type drive motors, or (2) the EPA, in accordance with Section 6 (e) (2) (B) of TSCA, authorizes the continued use of PCBs in the mining machinery based on a formal finding that such use will not present an unreasonable risk of injury to health or the environment. The Feb. 13, 1973 Decision of the Organization for Economic Co-Operation and Development (OECD), of which the U.S. is a member (Appendix C-1 contains a copy of this Decision), recommends that member nations ban the use of PCBs in all but four specific categories, one of which is mining machinery. This Decision might be cited by U.S. mining machinery owners as a precedent in petitioning for an exemption from the Toxic Substances Control Act. (Section 2.5 describes OECD).

A Directive of the Council of the EEC (European Economic Community, or Common Market), dated July 27, 1976, restricts member nations from using PCBs after January 1978 in all but six specific categories, one of which includes mining machinery. (Appendix C-2 contains a copy of this Directive.) The United States is not, of course, a member of the EEC, but owners and users of PCB-containing mining machinery in this country might cite the EEC Directive of July 27, 1976 as evidence of the importance of allowing continued use of currently operable PCB-containing mining machinery until the machinery is no longer operable.

The control of PCT imports and PCT use presents, however, a slightly different problem. Since it has been shown that polychlorinated terphenyls may contain between 0.5 and 10 percent PCBs (probably arising as a by-product in the manufacturing process), imports of PCTs might conceivably be treated as imports of PCBs, and the appropriate provisions of the Toxic Substances Control Act could then be applied to terminate importation.

A second control alternative for PCTs is to show that PCTs "present an unreasonable risk of injury to health or the environment", in which case the Toxic Substances Control Act would be applied as in the case of PCBs. The presence of PCBs in imported PCTs might constitute sufficient evidence of unreasonable risk of injury to the environment. It should be borne in mind, however, that pure polychlorinated terphenyls have not been shown to be a serious hazard to human health or to the environment, even though terphenyls are closely related to polychlorinated biphenyls and are highly persistent in the environment.

2.0 IMPORTS[1]

Imports of polychlorinated biphenyls during the years 1972 through 1976 came primarily from France, Italy and Japan, with small amounts imported from Canada and West Germany. All of the decachlorobiphenyl used in one manufacturer's casting waxes (until the middle of 1976) originated in Italy during these years, and the port of entry was Chicago, except one relatively small shipment to Philadelphia in 1972.

All of the polychlorinated terphenyl imported to the U.S. came from France during the years 1973 through 1976. The main ports of entry were New York, Philadelphia, Los Angeles and Baltimore.

In the following two sections, import data on PCBs and PCTs are discussed in detail in terms of volume, source and destination.

2.1 PCBs

Data from the U.S. Customs on PCB imports is shown in chronological order in Table 2.1-1. This information can be broken down in the following way:

	Total PCBs Imported	Decachlorobiphenyl Imported	Comments
1972	398,459 lbs	3,547 lbs	240 lb deca to Chicago 3307 lb deca to Philadelphia
1973	145,480	109,060	all deca to Chicago
1974	50,795	0	--
1975	198,415	149,914	all deca to Chicago
1976	113,581	0	all imports to Pittsburgh, Pyralene 3010

Since decachlorobiphenyl is no longer used in investment casting waxes, it is unlikely that large volumes will ever be imported again. All the imports in 1976 were Pyralene 3010 shipped from France to Pittsburgh where it is used as a motor coolant in mining machinery produced by Joy Manufacturing Company.

Imports of Pyralene 3000 and Pyralene 3010 to Pittsburgh have been as follows:

Table [illegible]

[illegible]

	QUANTITY					
TRADE NAME	POUNDS	METRIC TONS	COUNTRY OF ORIGIN	PORT OF ENTRY	ENTRY NO.	ENTRY DATE
Pyralene [illegible]	[illegible]	[illegible]	France	Pittsburgh	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	Japan	Baltimore	[illegible]	[illegible]
[illegible]	[illegible]	6	Japan	New York	[illegible]	[illegible]
[illegible]	[illegible]	6	Japan	New York	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	England	New York	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	Italy	Chicago	[illegible]	[illegible]
Decachlorobiphenyl	[illegible]	[illegible]	Italy	Chicago	[illegible]	[illegible]
Decachlorobiphenyl	[illegible]	[illegible]	Italy	Philadelphia	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	Japan	Los Angeles	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	Japan	Philadelphia	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	Japan	Philadelphia	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	Japan	Philadelphia	[illegible]	[illegible]
Pyralene [illegible]	[illegible]	[illegible]	France	Pittsburgh	[illegible]	[illegible]
Pyralene [illegible]	[illegible]	[illegible]	France	Pittsburgh	[illegible]	[illegible]
Decachlorobiphenyl	[illegible]	[illegible]	Italy	Chicago	[illegible]	[illegible]
Decachlorobiphenyl	[illegible]	5	Italy	Chicago	[illegible]	[illegible]
Pyralene [illegible]	[illegible]	[illegible]	France	Pittsburgh	[illegible]	[illegible]
Pyralene [illegible]	[illegible]	[illegible]	France	Pittsburgh	[illegible]	[illegible]
Decachlorobiphenyl	[illegible]	[illegible]	Italy	Chicago	[illegible]	[illegible]
Decachlorobiphenyl	[illegible]	[illegible]	Italy	Chicago	[illegible]	[illegible]
Decachlorobiphenyl	[illegible]	[illegible]	Italy	[illegible]	[illegible]	[illegible]
Decachlorobiphenyl	[illegible]	8	Italy	Chicago	[illegible]	[illegible]

Table 2.2-c (Cont'd)

VESSEL NAME	QUANTITY POUNDS	QUANTITY METRIC TONS	COUNTRY OF ORIGIN	PORT OF ENTRY	ENTRY NO.	ENTRY DATE
Pyralene 3010	25,926	11.76	France	Pittsburgh	[illegible]	3-12-74
Pyralene 3010	20,990	9.52	France	Pittsburgh	[illegible]	7-1-74
[illegible]	1,225	.56	France	New York	[illegible]	7-29-74
[illegible]	2,646	1.2	W. Germany	Jamaica	[illegible]	11-19-74
Pyralene 3010	20,650	9.37	France	Pittsburgh	[illegible]	2-13-75
[illegible]	17,637	8.0	Italy	Chicago	[illegible]	2-18-75
[illegible]	35,[illegible]	[illegible]	Italy	Chicago	[illegible]	2-18-75
[illegible]	11,220	4.[illegible]	Italy	Chicago	[illegible]	3-4-75
[illegible]	39,[illegible]	18	Italy	Chicago	[illegible]	4-29-75
[illegible]	39,[illegible]	18	Italy	Chicago	[illegible]	4-29-75
[illegible]	4,525	2.06	Canada	Buffalo	[illegible]	5-16-75
Pyralene 3010	20,990	9.52	France	Pittsburgh	[illegible]	8-22-75
Pyralene 3010	20,990	9.52	France	Pittsburgh	[illegible]	3-4-76
Pyralene 3010	30,864	14	France	Pittsburgh	[illegible]	5-27-76
Pyralene 3010	61,729	28	France	Pittsburgh	[illegible]	7-22-76

	Pyralene 3000	Pyralene 3010
1972	28,395 lbs	
1973	36,420	
1974	46,914	
1975	41,976	
1976		113,581 lbs

That the amount imported in 1976 was almost three times the amount imported in 1975, may indicate stockpiling in anticipation of an import ban. No other information is available at this time with respect to the finding of alternative materials for PCBs cooling fluids in mining machinery.

2.2 PCTs

PCT import data from U.S. Customs is shown in chronological order for the years 1973 through 1976 in Table 2.2-1. Import volumes for each of the years listed are as follows:

	Total PCTs Imported	Electrophenyl T60 Imported	Terphenyl Chlore T60 Imported
1972	0	0	0
1973	163,101 lbs	119,049 lbs three shipments to New York	44,052 lbs one shipment to Baltimore
1974	290,866	158,710 four shipments to New York	132,156 two shipments to Baltimore, one to Los Angeles
1975	273,375	218,212 four shipments to New York; two to Philadelphia	44,052 one shipment to Los Angeles
1976	275,576	231,484 three shipments to New York; two to Los Angeles; one to Philadelphia	44,092 one shipment to Los Angeles

Total terphenyl imports for the three years 1974 through 1976 have been about constant, with the import rate of Electrophenyl T60 increasing steadily while the import rate of Terphenyl Chlore T60 has correspondingly decreased.

[illegible]
[illegible]

[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]				
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Assuming all of the imported terphenyl goes into investment casting waxes, it is likely that all terphenyl entering the U.S. through Los Angeles probably goes to the single west coast terphenyl-wax manufacturer, J. F. McCoughlin Co., in Rosemead, California, though this company also purchases terphenyl from east coast importers. The remainder delivered to the east coast probably goes to Yates Manufacturing in Chicago and M. Argueso & Co., in Mamaroneck, New York, with a small amount going to Kindt-Collins in Cleveland, Ohio. West Coast terphenyl imports have increased dramatically in 1976: 44,052 pounds in 1974 and 1975, and 133,456 pounds in 1976. Again, this may be evidence of stockpiling in view of a possible import ban, but it might also indicate that either the other west coast wax producer is now using terphenyl also, or that other terphenyl uses have been initiated.

2.3 Importers

Pyralene for the Joy Manufacturing Company is purchased in France by a Joy subsidiary, Joy Ville-Goset, S.A., Paris, France, and shipped to Pittsburgh.(2)

Electrophenyl T60 is imported by at least one company, Intsel Corporation in New York City. The single customer of Intsel Corporation is Tivian Laboratories in Providence, Rhode Island, which distributes the terphenyl to three large wax producers: Yates in Chicago; J. F. McCoughlin, in Rosemead, California; and M. Argueso in Mamaroneck, New York.(3)

2.4 Discrepancies in Import Data

The import data reported above comes exclusively from the U.S. Customs. Additional import data have been gathered in response to Section 308 letters, but are not reported here since they do not cover the entire wax manufacturing industry. However, it can be stated that the Section 308 (P.L. 92-500, FWPCA 1972) responses contain information that is significantly different from the Customs data. For instance, Yates Manufacturing Company, according to its 308 response, purchased substantially more than 500,000 pounds of decachlorobiphenyl in 1974, though the Customs data indicate that none was imported that year. Also the 308 response of the single importer of terphenyl listed above, Intsel Corporation, indicates that the amount of terphenyl purchased in 1974 by M. Argueso & Co. was only one-third the amount Argueso states it purchased in that year.

These discrepancies may result from stockpiling of the material by the import distributor or distributors, so that the final users (i.e., the wax manufacturers) are purchasing the material years after it is imported. However, in the case of decachlorobiphenyl, Yates Manufacturing Company reported purchasing over one four-year period about five times the amount U.S. Customs reported was imported. Thus either there is an error in the reported data, or the material was being imported without it being recorded by Customs, or Yates was getting its material from a supplier (importer) not on record with Customs. For the purposes of this report, the Customs data is considered accurate.

2.5 PCBs - What Other Nations are Doing

All industrial nations face the problem of PCBs to some extent, and all are taking steps to control the flow of PCBs into the environment. The following is a discussion of PCB-related legislation and directives from Canada, the European Economic Community (EEC), and the Organization of Economic Co-Operation and Development (OECD, of which the U.S. is a member).

2.5.1 Canada

In December, 1975, the Canadian Government enacted "an Act to protect human health and the environment from substances that contaminate the environment"; its short title is the Environmental Contaminants Act. It is the Canadian equivalent of the Toxic Substances Control Act, though it does not specifically address PCBs as does TSCA.

In February of this year, the Canadian Ministry of the Environment promulgated, in accordance with the provision of the Environmental Contaminants Act, "Regulations Prescribing Certain Uses in Respect of Which Certain Chlorobiphenyls May Not Be Used". The Regulations was published in the Canada Gazette, the equivalent of the Federal Register, and is cited as the "Chlorobiphenyl Regulations No. 1", part 3 of which specifies that PCBs may not be used in the operation, servicing or maintenance of any product, machinery or equipment other than heat transfer equipment, hydraulic equipment and vapor diffusion pumps that were in use in Canada before March 1, 1977. The Regulation also allows continued use of PCBs in certain electrical devices, including transformers and capacitors.(4)

2.5.2 OECD

One of the on-going out-growths of the Marshall Plan is an international agency known as the Organization for Economic Co-Operation and Development (OECD). The OECD is an independent body consisting of the main industrial nations of Europe and North America (U.S. and Canada); it is the only organization of non-communist industrial nations.(5)

The OECD was established in December 1960 and currently consists of 24 members, primarily western European, but also including Japan, Australia, New Zealand, Greece, Turkey, and, of course, the U.S. and Canada, with Yugoslavia as an associate member. Funding contributions from member countries are based on GNP, with the U.S. contributing about 25 percent of the operating costs. Headquarters for the OECD is in Paris.(6)

The issue of PCBs has been before the OECD since the late '60s when various incidents in Japan and the U.S. made it evident that international controls were needed. PCBs are specifically addressed under the Chemicals Council of the Environment Committee which meets three times each year and reports to the Council of the OECD. Member nations submit information on imports, exports, usages and disposal practices of PCBs to the Environment Committee, and the Council of the OECD accordingly makes recommendations to the member countries.(4)

According to an OECD document issued in 1973, member countries other than the U.S. have been confronted with the same problems as the U.S. in finding suitable substitutes for PCBs. The PCB applications deemed most difficult to phase out and which the OECD considered temporarily permissible are:

Dielectric Fluids for transformers or large power factor correction capacitors

Heat Transfer Fluids (other than in installations for processing of foods, drugs, feeds and veterinary products)

Hydraulic Fluids in mining equipment

Small Capacitors, with the provision that special efforts be made in phasing them out most rapidly.

The single greatest advantage in using PCBs in the above applications is their combination of nonflammability and high dielectric strength. Appendix C-1 contains copies of the high points of the decision of the Council of the OECD adopted February 13, 1973.

On July 27, 1976 the Council of the European Economic Community (EEC) issued a Directive "on the approximation of the laws, regulations and administrative provision of the Member States relating to restriction on the marketing and use of certain dangerous substances and preparations". The United States is not, of course, a member of the EEC, but to the extent that the U.S. and the EEC are confronted by similar problems — specifically, in this instance, the problem of PCBs — the European efforts at controlling PCBs are worth noting and comparing to our own efforts. The July, 1976, Directive of the EEC makes the following comments and restrictions:

1. That polychlorinated terphenyls have been shown through "detailed examination" to entail risks similar to those presented by PCBs, and that the marketing of PCTs should also be restricted;
2. That the ultimate objective with regard to PCBs and PCTs is a complete ban; and
3. That the "designation of the substance, of the group of substances or of the preparation" shall include:
   - (a) PCBs except mono- and dichlorinated biphenyls,
   - (b) PCTs, and
   - (c) Preparations with PCB or PCT content higher than 0.1 percent by weight.

The Council of the EEC directs the restriction of the designated PCB/PCT preparations in all uses except the following categories:

1. Closed-system electrical equipment
2. Large capacitors (1 kg or more in total weight)
3. Small capacitors (provided that the PCB has a maximum chlorine content of 43 percent and does not contain more than 3.5 percent of penta- or higher chlorinated biphenyls); also, small capacitors not fulfilling this requirement may still be marketed for one year from the effective date of EEC Directive; and capacitors already in service are not affected by the directive
4. Heat-transfer fluids in closed-circuit heat-transfer systems (except in installations for processing food, animal feed, pharmaceuticals and veterinary products; if PCBs are used in these installations at the time of the EEC Directive, the uses may continue till the end of 1979 at the latest)
5. Hydraulic fluids used in:
    - (a) Underground mining machinery
    - (b) Machinery servicing cells for the electrolytic production of aluminum, until the end of 1979 at the latest.

A copy of the July 1976 directive is included in Appendix C-2.

Neither the Canadian Government nor the two international organisations, the EEC and the OECD, intend to permit the continued use of PCBs (or PCTs, in the case of the EEC) in tooling compounds or casting waxes. However, they all permit the continued use of PCBs, at least temporarily, in heat transfer applications of the type associated with the Joy mining machinery.

Bibliography - Section 2.0

1. Import records for PCBs and PCTs (including amounts, countries of origin, and ports of entry) for the years 1972 through 1976 were gathered from U.S. Customs through the office of U.S. Representative Les Aspin (D-Wisc.).
2. Telephone communication with Frederick W. Steinberg, Attorney with Rose, Schmidt and Dixon of Pittsburgh, Pa., representing Joy Manufacturing Co.
3. Importers and import distributors were identified through responses to Section 308 letters.
4. Canada Gazette Part III, Vol. 1, No. 12, pp. 1-21. 1974-75.
5. Telephone communication with Jack Thompson, Head of Multilateral Organizations, EPA Office of International Activities.
6. OECD and the Environment. Pamphlet published by the Organization for Economic Co-Operation and Development, Paris, 1976.

3.0 MINING MACHINERY COOLANTS

The port of entry for all PCBs imported in 1976 was Pittsburgh, Pennsylvania, where the Joy Manufacturing Company is located. The specific PCB formulation is called Pyralene 3010 and is imported from France where it is marketed by Prodelec.(1)

Pyralene 3010 is an intermediate-chlorinated biphenyl fluid. It is used by the Joy Manufacturing Company in the maintenance of a line of mining machinery that is no longer being manufactured. There are two specific types of machinery dependent upon PCB fluids, and in both types the function of the fluids is that of a nonflammable coolant for large alternating-current electric motors; a secondary function is that of bearing lubricant. The moving parts of the motors are totally immersed in the fluid, which by convection and conduction carries heat from the electrical windings to the external surfaces of the motor casing.(2)

The two types of mining machinery currently in the field are "loaders", of which a company spokesman estimated roughly about 350 are still operable, and continuous miners, of which there are about 50 still operable. The loaders use two motors and the continuous miners use three. Joy discontinued production of loaders using PCB-filled motors in early 1973; the continuous miners haven't been produced with PCB-filled motors since about 1970.(2) Production of these units was discontinued because of the PCB environmental issue.

An alternative fluid has not been found. The properties required are thermal stability, low viscosity, good lubricity, and compatibility with the motor windings. Joy currently sells, and is making an effort to market, a conversion kit for loaders. The kit converts the motor to a dry type requiring no heat transfer fluids. The difficulty in marketing lies in convincing longer available for maintenance procedures, as imports will soon be restricted by the Toxic Substances Control Act. The conversion kit costs about $6,200 per loader to purchase and install, and though some operators have had satisfactory results, reliability is generally less, and therefore overall operating costs have been higher.(2)

There are no equivalent conversion kits for the continuous miners because of space limitations. (The motors in continuous miners generate and must dissipate more heat than do the motors in the loaders; dry motors able to handle the heat load would be too large to fit on the present PCB-containing miners.) A Joy spokesman stated that the existing continuous miners might be fitted with new cutting heads that do not use PCB-filled motors; cost is about $65,000 per miner. Without such a modification, the 50 or so continuous miners using PCBs may have to be put out of service unless a suitable alternative fluid is found.(3)

Maintenance operations on PCB-filled mining machinery motors are performed by Joy in Bluefield, West Virginia. Spent fluids are loaded into the steel drums they arrive in and shipped to Monsanto in St. Louis where they are incinerated. Information on volumes shipped is not available.(4)

Joy also supplies machine owners with PCB fluids so that losses from the motors in the field (due to leaky seals and fluid overflow resulting from overfilling and subsequent heating and expansion of the fluids) can be replaced. There are no data on the amounts lost in mines.

All currently produced Joy mining machinery uses dry motors. The bulk of imports for the years 1972 through 1976 have been for maintenance of previously built machinery. All current imports have been entirely for maintenance purposes. The table below has been constructed from U.S. Customs data showing the amounts of Pyralene 3000 and Pyralene 3010 imported from 1972 through 1976:(1)

	Pyralene 3000	Pyralene 3010	% Increase Over Previous Year
1972	28,395 lbs		---
1973	36,420		+28
1974	46,914		+29
1975	41,976		-11
1976		113,881 lbs	+171

The large increase in 1976 over 1975 might be indicative of stockpiling in anticipation of import restrictions.

3.1 Portion of the Total Number of Mining Machines Containing PCBs

According to a publication of the National Mining Association,(5) in 1971 there were 2065 loaders made by various manufacturers in service. In 1974 there were 2151 loaders and 1959 continuous miners in service.(6) Thus, between 1971 and 1974, there was an increase of about 4 percent in the number of loaders; assuming a similar increase between 1974 and the present (1977) for both miners and loaders, the total numbers of loaders and miners currently in service are:

loaders = 2237
miners = 2037

Of these, the currently operable PCB-containing Joy units account for:

loaders = 350/2237 = 15.6%
miners = 50/2037 = 2.5%

3.2 Impact of the Toxic Substances Control Act

Joy no longer produces PCB-containing mining machinery; therefore it will not be adversely affected by the Toxic Substances Control Act. However, the owners of the PCB-containing machinery will be affected, since, unless exemptions are granted for mining machinery, the Act specifies that PCBs can no longer be used for open-system applications past the end of 1977.

Owners of loaders have three options available: (1) petition for an exemption, which, depending upon the interpretation of the Act, will allow one or more additional years of service from their loaders; (2) purchase and install the Joy-manufactured dry-motor conversion kit; and (3) scrap the loaders at the end of 1977. The second option will entail a certain initial cost (about $6,200 per machine (2)) and down-time for the machinery, but, except for a higher maintenance cost thereafter, the loaders will still be useable.

Owners of continuous miners also have three options: (1) scrap the machinery at the end of 1977, in accordance with the Toxic Substances Control Act; (2) obtain authorization from EPA for continued use of PCBs, assuming that it can be shown that this use of PCBs presents no health or environmental risks; or (3) purchase and install new dry-motor cutting heads (about $65,000 per miner). The practibility of the final option is a function of whether or not the installation of new cutting heads can appreciably extend the service life of the machinery.

It is probable that any mining company or trade association that petitions for an exemption might cite the July 27, 1976, Directive of the Council of the EEC. The EEC is also moving toward an eventual ban on PCB. Appendix C, directs member nations to terminate the use and manufacture of PCBs for all uses except for five specific categories, within one of which mining machinery is included.

In the event exemptions from TSCA are petitioned for, provision must be made for the maintenance of the PCB-containing machinery, which means PCB fluids will have to be available. Importation and stockpiling of PCB for maintenance of TSCA-exempt machinery will not be legal past the end of 1977.

The cost of replacing the 50 PCB-containing continuous mining machines, at an approximate cost of $300,000 each, will be about $15 million, which cost will be borne by the machine owners.

The response of Joy Manufacturing Company to the Section 308 questionnaire has been stipulated by Joy to be confidential. Thus the specific owners of the currently operable mining machinery, and the number of machines owned by each cannot be shown here. It should be noted, though, that the expected service life of a continuous mining machine of the type at issue is 10 years or more, and that the newest PCB-containing continuous miner is seven years old, and further, that though about 50 of these units are operable, not all are being operated.(2)

Bibliography - Section 3.0

1. U.S. Customs data obtained through the office of U.S. Representative Les Aspin (D-Wisc.).
2. Telephone communications with Prescott Green of the Joy Manufacturing Company, Franklin, Pa. Green provided all information on Joy uses of PCBs in mining machinery.
3. Telephone communications with C.W. Fitzgerald, Product Manager for Loaders and Continuous Miners, Joy Manufacturing Company, Pittsburgh, Pa.
4. Telephone communication with Stanley Butler of the Joy Manufacturing Company, Bluefield, West Virginia, Joy Maintenance. Disposal practices.
5. Telephone communications with David W. Pinkard, Editor, Mining Congress Journal; the number of loaders in 1971 was quoted by Pinkard from the publication of the National Coal Association, "1972 Bituminous Coal Data".
6. Telephone communication with Herbert Davis of the National Coal Association; Davis's numbers for continuous miners and loaders in 1974 were taken from publications of the U.S. Bureau of Mines.

4.0 TOOLING COMPOUNDS

Polychlorinated terphenyls are used in wax formulations known as tooling compounds, which are used to provide support to thin-walled objects so that they can be machined without buckling or otherwise being damaged. Most of the information on terphenyl-containing tooling compounds has been obtained from a patent held by the single manufacturer of terphenyl tooling compounds, from the response of this manufacturer to a Section 308 questionnaire, and from conversations with this manufacturer. Since specific information on the volume of tooling-compound sales might jeopardize this producers competitive position, no information will be reported here relating directly to sales volume. Terphenyl consumption in tooling compounds will be reported as an estimated percentage of terphenyl consumption in investment casting waxes.

As far as is known at this time, the only producer of terphenyl tooling compounds is M. Argueso & Co., Inc., of Mamaroneck, N.Y., which is also a major producer of investment casting waxes. A patent on terphenyl tooling compounds was taken out by Luis M. Argueso and Cyril S. Treacy,(1) listed as assignors to M. Argueso & Co. The patent application was filed in December 1961 and granted in April 1965. It is entitled "Method of Machining a Thin-Walled Object" (U.S. Patent No. 3,176,387).

To quote from the patent: ". . . the method and compound of the present invention may be utilized in the machining of any thin-walled object where the walls are subject to damage incident to the machining operation." An example of such an object is honeycomb structure fabricated from strips of metal such as steel or aluminum which are brazed or otherwise bonded into a hexagonal-cell honeycomb shape that has remarkable rigidity and very low weight. The thin walls of the cells of the honeycomb are, however, relatively fragile, and during cutting, routing, grinding or other machining operations these walls can be damaged. Damage to the cell walls will detract from the strength and rigidity of the honeycomb in a structural application. The function of a tooling compound is to provide support of the walls so they will not be deformed during machining. In the case of honeycomb structure, the tooling compound is used to fill the honeycomb cells until the machining operations are completed, then the compound is removed by heat or solvents or by a combination of the two.

Tooling compounds are not, of course, confined to use in the machining of metal honeycomb. They can be used to support any thin-walled object made of almost any material during machining, such as thin-walled tube made of plastic, glass, and even rubber or cardboard, according to the patent. The patent also claims coverage of a tooling compound that can be removed after the machining operation without the application of heat, as would be the method in the case of tooling compounds formulated from high-melting waxes or low-melting alloys. The tooling compound claimed in the Arquesso patent is soluble in "aqueous solution at substantially ambient temperature." Arquesso's tooling compound is introduced into the structure in a molten form, "which has no adverse effects on the unmachined article." The advantage of this formulation is that it can be removed without the application of heat to the machined object because of the potential adverse effects of elevated temperature on the machined object. "Upon completion of the machining operations, the compound within the interstices or cores may be removed by subjecting the object to an aqueous acid solution at room temperature which effectively removes all traces of the compound from the object and leaves no film of the compound on the walls of the object with no residual effect on brazing or other similar properties."

The principle ingredient in Arquesso's tooling compound is a water-soluble wax, specifically polyethylene glycol having a molecular weight of from 4000 to 20,000. Secondary ingredients are metallic carbonate ($NaHCO_3$, $CaCO_3$ are two cited in the patent) and finely divided mica and/or spun glass fiber. The following sample formulations are among ten recipes listed in the patent:

Polyethylene glycol (6000 molecular weight)	70% (weight)
Very fine water-ground mica	10
$NaHCO_3$ (precipitated, very fine)	20

Same as above, but with polyethylene glycol having a molecular weight of 4000

Polyethylene glycol (6000 molecular weight)	42%
Very fine water-ground mica	10
Chlorinated terphenyl (Aroclor 5460)	8
$NaHCO_3$ (precipitated, very fine)	40

Polyethylene glycol (20,000 molecular weight)	14%
Polyethylene glycol (6,000 molecular weight)	56
Very fine water-ground mica	10
$CaCO_3$ (precipitated, very fine)	20

Polyethylene glycol (20,000 molecular weight)	14%
Polyethylene glycol (6,000 molecular weight)	56
Very fine water-ground mica and spun glass fiber	10
$CaCO_3$ (precipitated, very fine)	20

Polychlorinated terphenyl is cited in only one of the ten example formulations given, and it is covered specifically only in claim 16 of the 22 claims made in the patent. In the sample formulation, which is shown above, terphenyl is shown as constituting only 8 percent of the mixture. This same 8 percent figure is also stated specifically in claim #16.

Argueso's response to the Section 308 questionnaire states, however, a much higher percentage of terphenyl, a percentage which would be stated here if it were covered by the patent or otherwise public knowledge. It is likely that M. Argueso & Co. produces several lines of tooling compounds, not only the aqueous-soluble variety, but of the type that must be melted out of the work piece being machined. The reason for saying this is that polychlorinated terphenyl is insoluble in water, and in the high percentages Argueso says is used in tooling compounds (much more than 8 percent), dissolution of the tooling compound in aqueous solution at substantially room temperature would be extremely slow.(2)

The amount of terphenyl sold in tooling compounds by Argueso is on the order of about 2 or 3 percent of the volume of terphenyls sold in investment casting waxes by the entire investment casting industry.(2) Still Argueso says there is no adequate substitute for terphenyl in tooling compounds.(3) Of the ten sample tooling compound formulations shown in his patent though, only one lists terphenyl as an ingredient, and only to an extent of 8 percent by weight.

Bibliography - Section 4.0

1. U.S. Patent #3,176,387, Method of Machining a Thin-Walled Object. Luis Argueso, April 6, 1965.
2. Section 308 response: M. Argueso & Co., Mamaroneck, N.Y.
3. Telephone communications with Luis Argueso, Vice President, M. Argueso & Co.

5.0 THE INVESTMENT CASTING INDUSTRY

In the following discussion the investment casting industry is examined in terms of the present state of the investment casting art, the advantages of investment casting and the limitations. The technology of the investment casting waxes is also examined, and alternative waxes and alternatives to wax are considered.

5.1 Introduction to Investment Casting

Investment casting is a method of producing very precise metal castings; that is, castings having high surface finish and close dimensional tolerances. Investment casting is also known as lost-wax casting, lost-pattern casting, hot investment casting and precision casting.

In general, casting consists of introducing molten or fluid materials into a mold where, upon solidification, they acquire the internal shape of the mold. The advantages of casting compared to other methods of metal forming such as machining, forging, and extrusion is that casting can be used to mass produce intricate shapes at a considerable cost savings over the other metal forming methods. Materials can be cast in pieces weighing from fractions of an ounce to tens of tons.

There are four types of casting processes: sand casting, permanent mold casting, die casting, and centrifugal casting.(1) Each method will be touched upon briefly here; a more detailed discussion will be included later when the various casting methods are compared to investment casting on an economic basis. Investment casting is considered a form of sand casting known as aggregate molding.(1)

The products produced by investment casting have the highest dimensional accuracy and smoothest finish that can be produced by any casting process. The process is also not limited by the melting point of the metal to be cast - if a metal can be cast at all, it can be investment cast.(2) The chief limitation is weight of the casting; the process can be applied most advantageously to castings weighing less than 10 pounds, though castings weighing as much as 100 pounds have been produced.(3)

The root of investment casting, i.e., to invest, means in this context "to cover completely, to envelop". That which is enveloped or invested is the pattern out of which the investment casting mold is made. The pattern in investment casting is referred to as expendable, because it is destroyed by the time the mold is ready for the pouring of molten metal. The pattern material is wax or some combination of wax and other ingredients, and it is invested with, or covered with, a refractory coating that hardens at room temperature. The wax, or in general, thermoplastic pattern material (including plastics such as polystyrene), is then melted and/or burned out of the refractory mold which is then raised to a high temperature in preparation for metal pouring; the cavities in the mold duplicate the dimensions of the thermoplastic pattern to within several thousandths of an inch. The products cast by the investment process are of such high dimensional quality and surface finish that they require little or no machining once they are broken out of the mold and cut away from the sprues, gates and runners. (Appendix A contains a diagram in which such terms as sprue and gate are defined. See also Figures 5.1 and 5.2.)

Investment casting can be viewed as two casting processes combined: the patterns are made by a die casting process, and in that sense are themselves castings, and then they are invested with ceramic material in order to make the ceramic mold for the actual metal casting process. As a method of metal forming lost-wax casting is among the oldest known. Whereas the oldest known sand mold has been traced to 645 B.C., and it is known that the Chinese cast iron as long ago as 800 to 700 B.C., investment or expendable pattern molding has been in use in one culture or another for more than thirty-five hundred years. This is not to imply, however, that investment casting is the oldest known casting method, though it apparently did predate the casting of iron in sand, or in any medium for that matter. There is evidence of copper casting in Mesopotamia some 6000 years ago.(4)

(An interesting note on the casting of iron is that while in western cultures castable iron was not melted until within the last few centuries, the Chinese developed a system of "box bellows" that could supply sufficient draft and heat for the melting of iron more than 2500 years ago. The Chinese had also discovered that iron heated with carbon in a highly reducing atmosphere melts at a much lower temperature (2138°F) than does purer iron having less carbon content (2786°F).)(4)

Investment casting is best suited to the production of a large volume of small (on the order of several ounces), intricate parts made of metals that are otherwise difficult or impossible to machine. Examples are turbine blades, gun and machine parts, nozzles for high temperature jets, and parts for household appliances. The high cost of producing the pattern dies (discussed below) which must themselves be cast from metal or machined out of metal, and the high capital cost of the investment casting support equipment, is offset by the small amount of finishing operations and machining required for the final cast product.(1,5)

The pattern is possibly the most critical part in the investment casting process. As the alternative name for the process - i.e., lost-wax process - indicates, wax is an essential ingredient in investment casting; specifically, wax is the material from which the pattern or patterns are made. The wax - or, in general, the pattern material - must have certain properties, the most critical of which is dimensional stability as a function of temperature. Ordinary wax shrinks upon cooling from a liquid to a solid and it continues to shrink in the solid phase as the temperature is further reduced. The main function of polychlorinated biphenyls and polychlorinated terphenyls in investment casting waxes is to improve the dimensional properties of waxes as a function of temperature.(6,7)

5.1.1 Making the Dies for the Production of Wax Patterns

Dies for producing wax patterns can be made either by machining cavities in two or more matching blocks of steel or by casting a low-melting-point alloy around a higher-melting-point metal master pattern. Ordinarily the dies consist of two parts, which separate in order to remove the wax pattern. The life of a steel-machined die is considerably longer than that of a softer low-melting-point alloy, though once a metal master pattern has been made, low-melting-point dies can be readily reproduced. To make such a die, the metal master pattern is first imbedded in plaster or clay to its parting line, which provides proper draft in each half of the die. After applying a parting material and placing a "flask" over the upper, or exposed part of the master pattern, to contain the metal to be poured, the low-melting-point alloy is poured, thus producing one half of the pattern die. The other half is made by applying a parting material and pouring molten alloy into a flask over the master pattern resting in the previously completed die half. Alignment dowels and corresponding holes in the die halves may be cast by first drilling two suitable holes in the parting surface of the first completed die half. When the opposite side is cast, the corresponding pins will be cast. The gate through which the wax is to be injected is then drilled or machined at the parting, providing draft for the opening of the die and removal of the wax patterns.(8)

3.1.2 Production of the Wax Patterns

The two halves of the pattern die are clamped together and wax is injected into the die cavity at pressures ranging from 100 to 2000 psi. Depending on the characteristics of the wax it may be injected in the liquid state, the mushy or slush state (between liquidus and solidus), or in the solid state at a temperature just below its melting point. To provide adequate venting, small shallow vents may have to be cut in the parting surface of one of the die halves. Shrinkages in larger sections of the wax pattern during cooling may cause surfaces to sink (a process called cavitation), because all wax formulations shrink on cooling. Shrinkage problems may be overcome by the application of compressed air at about 100 psi to the injection gate shortly after injecting the wax, or by maintaining the injection pressure on the wax in the die until it is sufficiently cooled for the pattern to be removed.(5) Most quantity production of wax patterns is by automatic injection machines offering close control of temperature, pressure and speed of injection.(3)

According to Beeley,(3) polystyrene patterns are less expensive to produce than wax patterns. Polystyrene patterns are also superior to wax in that they are less fragile, they have better surface-finish properties, and they can be handled more readily without deterioration.(2) The cost advantage of polystyrene has, however, decreased since the 1973 rise in petroleum feedstock prices. The disadvantages of polystyrene compared to wax are: higher injection pressures are required in making the patterns (up to 20,000 psi vs about 400 psi for wax), steel pattern dies are required because of the higher injection temperatures, higher pattern production rates are possible for wax patterns and the pattern mold for plastic patterns must have and hold the highest surface finishes because plastic patterns can hold a better surface finish than wax.(5)

The production of wax and polystyrene patterns has many problems similar to those experienced in metal casting. Injection speed must be designed to avoid flow marks or misrun patterns and mold-entrapped air. There is also the possibility of deformation of the patterns because of residual cooling stresses.

5.1.3 Pattern Assembly

Figures 5.1 and 5.2 show the differences between the investment shell and the investment block methods of investment casting. Investment shell molds are precoated in a very fine ceramic slurry which is subsequently backed by coatings of coarser ceramic materials, but in the investment block method a fine-grain ceramic material is used throughout the entire investment. If the pattern material is plastic (polystyrene), the investment block method is used instead of the shell method, because the block mold is stronger and can better withstand the stresses generated in the removal of the plastic pattern (polystyrene has a higher coefficient of thermal expansion than wax).(2,3)

Most products cast by the investment casting process are small enough that the patterns can be assembled in large numbers on a single "tree" so that many castings can be poured simultaneously. The wax patterns can be easily fastened to a gating system also made of wax. The fastening or "welding" process is carried out with heated spatulate tools or small gas torches that heat and melt the wax surfaces to be joined. To reduce the time required for this assembly operation, an assembly fixture may be employed to hold the patterns in place while molten wax, usually previously-used pattern wax, is poured into the fixture and allowed to solidify thus producing the sprue and gating system as one unit with the patterns. The assembled wax tree is removed from the fixture after the wax solidifies. This fixture method entails a tooling cost that is greater than that

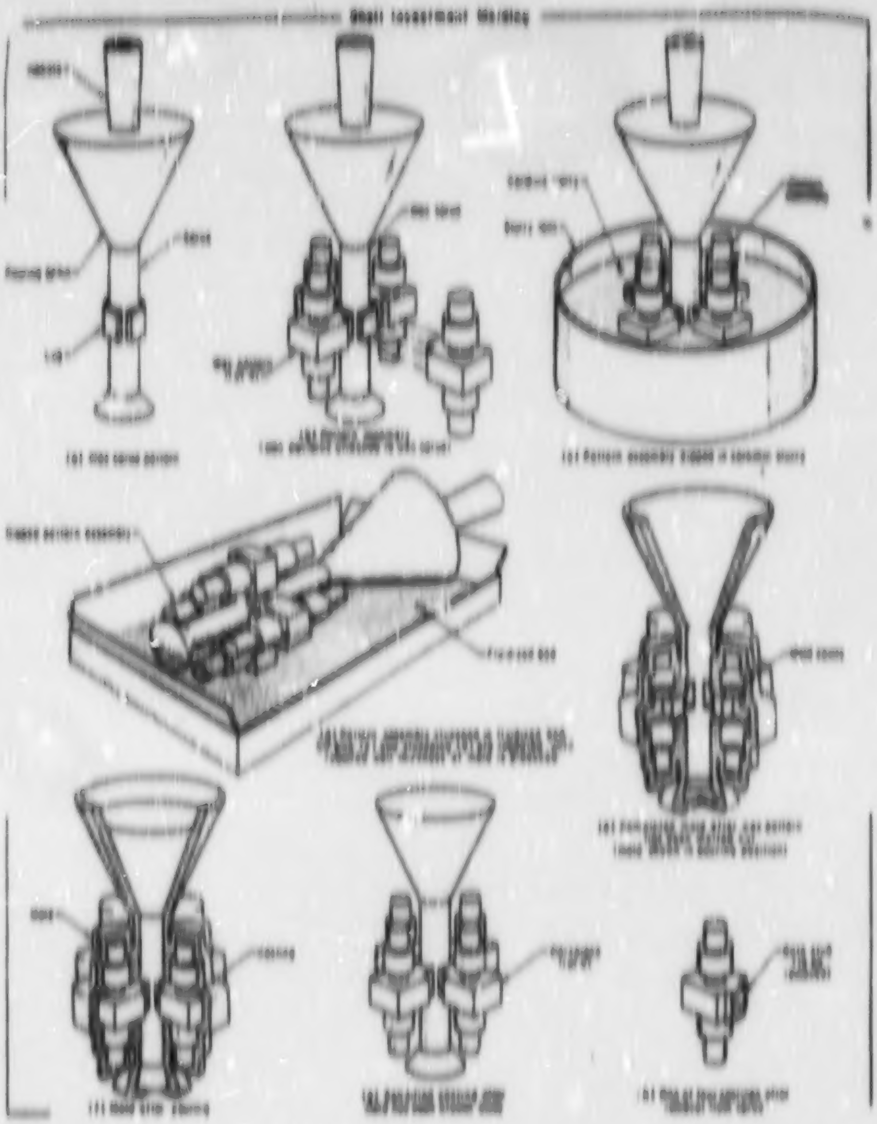

Figure 5.1

Steps in the Production of a Casting by the Shell Investment Molding Process.*

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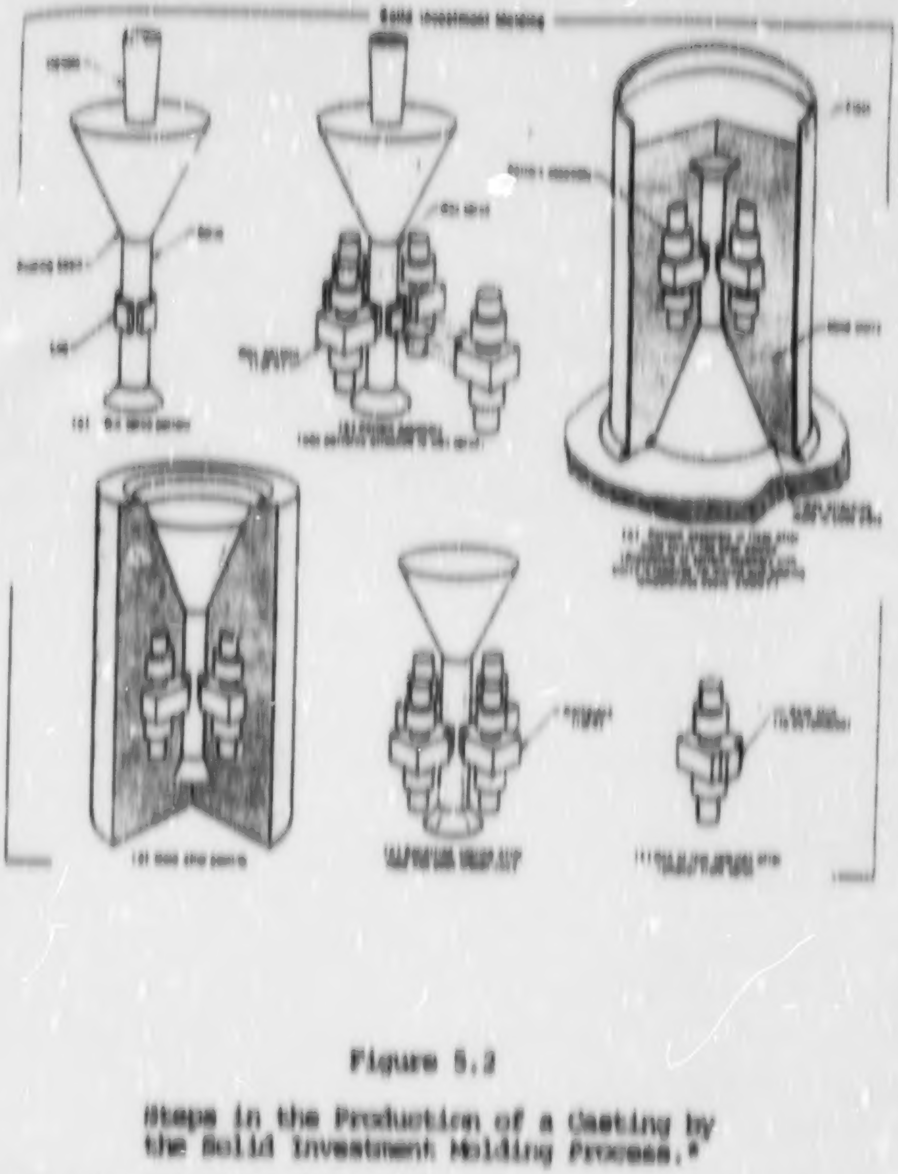

Figure 5.2

Steps in the Production of a Casting by the Solid Investment Molding Process.*

*By permission from Metals Handbook Volume 5 Copyright American Society for Metals, 1970 of hand assembly of the patterns onto precast sprue and gating systems, but for large quantities of parts the fixture method can be less labor intensive.(8)

Figures 5.1 and 5.2 show the pattern assembly process, but without a holding fixture. Wax patterns can also be assembled by the "dip seal" method whereby the gate lugs on the wax patterns are dipped in molten wax (which is usually used wax from previous patterns) then quickly stuck to the lugs on the sprue assembly. Polystyrene patterns can be glued with plastic cement or by moistening with solvent. Patterns are packed as closely as possible for maximum production, but not so close as to interfere with proper cooling of the castings.(5,8)

5.1.4 Investing the Wax Patterns and Producing the Ceramic Molds

The assembled "tree" of wax patterns is surrounded with, or invested with, refractory mold material, and, as mentioned above, the final mold is either a monolithic block or a shell of built up layers of cermaic material. The block-mold process, also called the solid-mold or flask-mold process, is the more traditional one, but in the last few years automation has made the shell-mold method predominant with the block-mold process being reserved mainly for the casting of parts requiring higher as-cast surface finish.

In general, the shell and solid mold processes do not differ appreciably, if at all, in pattern preparation or pattern assembly. However, patterns for the shell process are always given a precoat of fine ceramic slurry, whereas precoating of patterns for the solid process is generally not required unless the properties of the backup refractory are inadequate for the special application. Precoating methods for both processes are similar: the pattern is dipped in a fine ceramic slurry, and a granulated refractory is applied by sprinkling, by means of a fluidized bed, or by other suitable method.

In the shell investment process, after precoating, the pattern assembly is alternately dipped in a coating slurry and "stuccoed" with granulated refractory, either by sprinkling or by suspending it in a fluidized bed, until the shell is built up to desired thickness. Usually, the refractory grain ranges in size from 20 to 100-mesh, the fine material being used for the initial coat and progressively coarser grains for subsequent coats. Since the fineness of the initial investment slurry determines the surface smoothness of the final castings, the precoatings are usually made of extremely fine refractory grains on the order of 300 mesh suspended as a slurry in a suitable binder. Each coat of slurry and grains is air dried before the following coats are applied. Shell thicknesses are on the order of 1/4 inch.(5)

In the solid investment process, the pattern assembly (precoated if it is to be used for the casting of high-temperature alloys - i.e., above 2000°F) is encircled by a flask which, in turn, is filled with a refractory mold slurry.(5) The mold slurry, called a "backup slurry", and the flask together with the pattern assembly in it is vibrated for about an hour to settle the investment material and cause air bubbles to rise away from the pattern. After air-drying for about 8 hours, the investment hardens.(8)

The principle refractory used for investment materials is silica, either quartz or cristobalite. For metals with pouring temperatures below 2000°F the commonly used binder is gypsum plaster. For higher pouring temperatures, a high-temperature cement, or a binder such as ethyl silicate, must be used.(8)

5.1.5 Removing Wax Patterns from the Ceramic Molds

The most common method for removing patterns from molds is to melt the pattern. However, the thermal expansion of the wax exceeds that of the ceramic mold by a factor of about 10,(8) and unless the melting is carried out in the proper way, the mold can be cracked or broken. Although the amount of expansion varies among different waxes, the volume can increase as much as 10 percent before the wax melts.(5)

To increase the strength of the shell to prevent it from breaking under the wax pressure would be self-defeating. The thicker mold would be harder to remove from the finished castings. A heavier mold would not dissipate heat from the molten metal as well as would a thinner shell, possibly resulting in hot tears in the castings. (Block-type molds can withstand considerably more internal pressure during melt out than can the shell type). The only practical methods for preventing mold breakage during wax removal are: (a) supplying external pressure to the shell to counterbalance the internal pressure of the wax;

and (b) rapidly dissolving or melting a skin or surface layer of wax at the interface of the ceramic shell mold and the wax pattern, thereby creating a cavity into which the remaining wax can expand.(5)

5.1.5.1 Dewaxing of Shell Investment Molds

In one method of external pressure application, the ceramic shell mold and wax-pattern assembly is placed, pouring cup down, in a container that has a hole in the bottom. The mold is positioned so that the pouring cup is directly over this hole. Sand or some other granular or powder refractory (or metal shot), heated to about 600°F is then poured around the shell, and the container is vibrated to pack down the refractory medium as quickly as possible. A continuous supply of hot refractory is required to operate the process on a production basis. The container, filled with the hot refractory, is set aside until the wax has melted out of the shell, after which the shell is ready to be fired. The shell may be fired in the container, supported by the backup refractory, or it may be removed from the backup and fired unsupported. Less firing time is required if the latter method is used. The wax collected from the mold can be re-used after it has been filtered or centrifuged to remove refractory particles.(5)

The pressure applied to the shell depends on the depth to which the shell is buried and the packed density of the refractory surrounding it. The shell must not come in contact with the heated refractory at too high a temperature if the packing is slow; otherwise, heat conducted through the shell will begin to expand the wax before the full external pressure has been applied. A temperature range of 500 to 750°F for the refractory or shot is suitable for most normal vibrating methods of packing and produces crack-free shells. Wax recovery by this method is high, because the wax is subjected to only moderate heating and can be re-used after careful elimination of refractory particles.(5)

An alternative to the packed hot refractory method is a heated fluidised bed. The bed is fluidised and the shell is placed in it with the pouring cup up. The air is turned off to allow the refractory material in the bed to settle and pack around the shell. After the wax has melted, the bed is refluidized, and the shell is removed and rapidly inverted to pour out the wax.(5)

Flash dewaxing is widely used to remove wax from shell-type molds. In this method the shell molds are placed in a furnace hot enough to establish a high thermal gradient across the ceramic shell, thus causing the wax to melt at the wax-ceramic interface before the volume of the wax heats and expands appreciably. Low thermal conductivity of the wax is an advantage of this phase of the ceramic mold manufacturing process. The temperature of the furnace in flash dewaxing is 1800 to 2000°F. The time interval for loading shells into the furnace must be regulated to avoid heating the shells too slowly. A slow heating rate will expand the wax without melting it and may crack the shell mold. For example, a shell produced under controlled conditions at 80°F will crack in 10 to 15 minutes at 100°F. In general, flash dewaxing takes 10 to 20 minutes, depending on the shape and thickness of the mold. After dewaxing, the shells are either transferred to a holding furnace for casting or they are cooled for inspection, patching, or additonal dips in the slurry.(5)

Flash dewaxing generates considerable amounts of smoke, so ho[illegible] and exhaust systems are essential. Often, the water container placed under the furnace to collect molten wax overheats, boiling the water and igniting the recovered wax. The fire hazard, the generation of smoke and the volatilization of potentially dangerous wax components and fillers are major disadvantages of flash dewaxing.(5)

The most commonly used method of dewaxing is by use of a steam autoclave. As with the other thermal dewaxing methods, the object is to deliver heat as rapidly as possible to the interface between the wax and the mold so that melting can start there before the main body of the wax starts to heat and expand. Autoclave dewaxing takes advantage of the latent heat of vaporization of steam to deliver sudden heat to the surface of the mold.(5)

A typical autoclave operates at 320 to 325°F and 90 to 100 psi. It is jacketed to maintain the temperature of the vessel during loading and unloading operations. During the dewaxing cycle, shells are loaded onto a sliding tray and passed into the autoclave through a fast-operating door equipped with a safety lock to prevent accidental opening during the pressure cycle. Loading the shells, closing the door, and pressurizing the vessel to 80 psi is accomplished in about 10 seconds. Average processing time for a complete cycle is about 10 minutes. Under normal conditions, between 85 and 95 percent of the wax is recovered. Since the process is inherently low-temperature, and since the autoclave is sealed until the dewaxing process is completed, the used wax is less likely to be rendered unusable by high temperatures and the amount of wax volatilization and smoke generation is negligible.(5)

Dewaxing can also be accomplished by use of a hot-wax bath at 425 to 450°F. The ceramic shell molds to be dewaxed are placed, pouring cups down, on a wire or expanded-metal basket and are lowered either immediately or in steps into the liquid wax bath. Complete dewaxing takes place in 5 to 30 minutes, depending on the mold size and shape and the type of loading sequence. Temperature control of the liquid wax bath is important; if the bath temperature falls below 425°F, a high percentage of shells will crack because, as mentioned above, too much of the wax inside of the mold will heat and expand before melting takes place at the wax-mold interface. Overheating of the wax bath can cause fire.(5)

There are nonthermal methods of dewaxing in which solvents are used to dissolve the wax from the mold, or at least from the wax-mold interface so that subsequent wax melting procedures will not cause cracking of the mold if the absorption of heat into the wax proceeds too slowly. Heated trichlorethylene vapor, for example, has been used to permeate the porous ceramic shell and dissolve the wax at the interface; the remaining wax can then melt out without damaging the mold. The molds are normally supported in a wire tray with the pouring cup down. During the latter stages of dewaxing, the wax patterns melt and run into the reservoir of solvent.(5,6)

Solvent dewaxing is slow, requiring about 30 minutes for large patterns, and if penetration of the ceramic is too slow, premature wax expansion can occur and crack the molds. Equipment for solvent dewaxing consists of a conventional trichlorethylene vapor machine of the type used for vapor degreasing. In time the wax accumulates in the bottom of the tank in solution with the trichlorethylene. When sufficiently concentrated, wax recovery is by distillation. This is done in the same equipment used for dewaxing; the trichlorethylene, which condenses on the cold-water pipes at the top of the tank, is prevented from running back into the reservoir by collecting it in gutters below the cold-water pipes.(5)

In a patented solvent dewaxing method, a cold solvent is used for removing wax from the shell mold after the third or fourth coat of ceramic material has been applied and dried. The solvent penetrates the shell, and dissolves and removes a thin layer of wax at the interface. Additional coats of ceramic are then applied. This method was originally applied for removing plastic patterns (i.e., made from a polystyrene thermoplastic composition) from shell molds.(5)

5.1.5.2 Dewaxing of Solid Investment Molds

Although shell-type molds are used far more than solid-type or flask-type molds these days, solid molds are still used for the casting of very small and intricate pieces for which polystyrene is the best pattern material.(2) (Because polystyrene expands on heating more than wax, the additional strength of the block-type molds is required when using plastic patterns.) Mold cracking caused by expansion of the wax is not a problem in dewaxing of solid molds, because of the backing provided in the solid mold. In practice, solid molds are dewaxed (or deplasticized), burned out (fired), and preheated for pouring in a single cycle.

Initial heating is critical. Heating too rapidly while large amounts of free water remain in the mold can cause the formation of steam pockets between the precoat layer and the backup investment. Pieces of precoat may break away from the backup coat, allowing molten metal to flow in between and form a "scab" on the casting. To provide slow initial heating, the molds are placed in a gas-fired or electric furnace, usually of the tunnel type. The molds are introduced at the low-temperature end (not more than 800°F) and are slowly moved through the furnace to higher-heat zones (up to 2000°F). The wax or plastic melts out of the mold and is burned off as the mold advances through the furnace, and the mold emerges from the hot end preheated and ready for pouring. Wax reclamation is possible with this method, though it is not usually considered practical.(5)

As with shell dewaxing, thorough burnout is very important since any wax residue not removed shows up as carbon black in the investment around the mold cavity and usually causes defective castings from failure of the mold to fill with metal. The mold should remain at the maximum temperature for 2 to 4 hours depending on the size of the mold and the amount of organic matter to be burned out.(5)

5.1.6 Firing and Preheating the Molds

Most investment molds must be preheated prior to pouring to:

1. Burnout residues of wax and/or plastic
2. Permit metal filling of mold sections too thin to be filled in a cold mold
3. Minimize the size of risers (Risers are internal reservoirs of molten metal in the mold; they supply liquid metal to the actual castings which, as they solidify from their outer surfaces inward, shrink and must be fed additional metal.)
4. Minimize hot tearing during cooling of the cast metal

Furnaces used for firing and preheating of molds are either of the continuous type or batch type. Continuous furnaces of either the pusher or rotary type provide a continuous supply of preheated molds. They are efficient for high-production operations because they can be divided into temperature zones that provide optimal heating schedules. A typical continuous furnace used for heating solid molds has four zones of heating:(5)

Zone 1. The mold is dewaxed, thus eliminating the need for a previous dewaxing operation. The temperature of this first zone may range from 300°F to 800°F.

Zone 2. Temperature is increased to an intermediate range, usually from 1400°F to 1500°F.

Zone 3. Maximum temperature, about 1800°F (steel castings); wax residue is completely removed in this stage.

Zone 4. Molds are held at the same temperature or slightly lower than in the previous zone until pouring.

Batch-type furnaces for firing and preheating are generally similar to those used for metal heat treatment. Molds are dewaxed in a previous operation (e.g., by autoclave). Batch-type furnaces are maintained at the desired preheat temperature. Molds are loaded to the capacity of the furnace. When the furnace has stabilized at the set preheat temperature and the molds have remained at temperature for the required time (sufficient to burn out organic residues and to achieve thermal equilibrium), pouring can begin. Preheated molds are withdrawn from the furnace as they are required by the casting operation. When the furnace has been completely emptied, it is reloaded with cold molds and the cycle is repeated.(5)

5.1.6.1 Furnace Operation and Temperature

The same furnaces can be used for preheating ceramic shell mold and solid molds, but the heating cycles are greatly different. A shell mold will have been dewaxed prior to preheating and will have a weight that is only a fraction of that of a comparable solid mold; also, a shell is made of materials that can stand the thermal shock of being placed in a preheated furnace at 1500° to 2000°F. Thus, the same furnace can preheat several times as many shell molds as solid molds.

Preheat time for shell molds ordinarily ranges from 1/2 to 2 hours. When shell molds are backed with a dry refractory material, preheat time is on the order of 3 to 5 hours.

Furnace atmosphere must be oxidizing at all times to ensure complete elimination of all organic material. It is common to provide air 10 percent in excess of the amount theoretically needed for complete combustion.

5.1.6.2 Mold Preheat Temperature

Although many investment molds are poured at room temperature, more often the molds are preheated before pouring. Preheat temperatures range from 200° to 1900°F, depending on the type of metal being poured.

For each casting metal, there is a mold temperature range that is most commonly used, depending on casting size and complexity. For instance, aluminum alloys are usually poured into molds preheated to 400° to 650°F. But, depending on the particular casting, mold temperature for aluminum alloys may range from 70° to 1000°F.

The advantages of high preheat temperatures are:

1. Reduced possibility of misruns or cold shuts in complex castings or those having extremely

thin sections, particularly when the castings are gravity fed.

2. Reduced thermal shock to the mold.

The disadvantages of high mold temperature are:

1. Increased possibility of local shrinkage, especially in thick sections, because of the slower cooling rate.
2. Greater possibility of evolved gases, which are likely to cause porosity of the casting.
3. Adverse effect on mechanical properties for some alloys, because of the slower cooling rate.
4. Longer cooling time required for removal of the casting from the mold.

5.1.6.3 Wax Losses to the Environment During Firing and Preheating

After the dewaxing process and prior to the mold firing operation, the mold contains a certain amount of wax that is either in the form of small puddles inside the mold or it is contained within the porosity of the mold material. The amount of wax remaining in the mold may vary from 0.1 to 15 percent.(6,7,9) Considering that the ceramic molds are porous and that the wax acquires very low viscosity during the melt-out process, it seems likely that the mold could well become saturated with wax during meltout. Certainly the complexity of the part being cast and the number of patterns making up a given mold would influence the amount of wax that would not come out of the mold during dewaxing. In any case, the highest industry estimates for wax remaining in the molds prior to firing is about 15 percent, and of that wax remaining, between 20 and 70 percent of it is filler materials or additives.

Decachlorinated biphenyls were used till the middle of 1976 as a solid filler material in many investment casting waxes. PCBs are no longer used as such, but polychlorinated terphenyls are being used and have been used for more than 20 years as a component of some wax formulations. Polychlorinated terphenyls are no longer manufactured in the United States; all PCTs currently used in this country originate in Europe. The sole distributor of PCTs in the U.S., however, is currently certifying that their PCTs contain less than 0.05% PCBs. (The previously used American PCTs have been measured to contain about 0.5 percent PCB contamination.) Thus, to the extent that PCTs contain PCBs, they are environmentally dangerous above and beyond the intrinsic hazard of PCTs alone. The content of PCTs in PCT-containing waxes is on the order of 40 percent.(6,7,10) Thus, 40 percent of whatever wax remains in the yet-to-be-fired molds is PCT, of which a small percentage may be PCB of unspecified chlorination level.(11)

The furnace temperatures at which molds are fired and preheated range up to 2000°F. The amounts of PCTs and PCBs that can escape the furnace range from zero or infinitesimally small to the full amount contained in the mold prior to firing. The low estimates are based on the premise that the volatilized wax and its components and fillers are exposed to the highest temperatures for periods of time sufficient to completely destroy the PCBs and PCTs, and reference is made to the fact that the molds are heated for periods of hours before removal from the furnace.(6) (The long stay in the furnace is, of course, intended to assure complete oxidation of organic material in the mold.) The higher estimates are based on the [illegible]ion that the bulk of the losses to the environment take place during the initial mold heating phase, when the wax and its components and fillers volatilize from the still-relatively-cool mold and are carried upward through the flue in pockets of relatively cool gas. As far as is known, no one has actually performed an analysis on the flue gases emanating from investment foundry furnaces during firing and preheating.

Since most foundries use autoclave dewaxing these days,(2,5) the main process source of potential pollutant generation is the mold firing operation where volatiles might be lost up the stack. Other sources of environmental hazard from wax additives and fillers lie outside the foundry process – i.e., during wax disposal operations, which may include incineration and non-secure landfilling, and during wax reclamation carried on by wax manufacturers.

5.1.7 Metal Casting

After the molds have been fired and preheated, molten metal is poured into the molds while they are supported in suitable fixtures. After the metal hardens and cools, the ceramic mold material is removed by various methods including hydroblast, pressurized air blast or power chisels, or combinations thereof, and in some instances powerful acids are used to dissolve small cores out of the castings. (Silica cores as small as 1/16th inch are dissolved out with hydrofluoric acid.) The individual castings are then cut from the cast tree assembly and finishing operations are performed as needed – e.g., the grinding off of gate lugs, machining, plating.

5.2 Advantages and Limitations of Investment Casting

Generally speaking, the advantage of investment casting is that it is the most cost effective way to produce high quality castings out of *any* castable alloy. If a metal can be cast, it can be investment cast.(2) Investment casting is the only metal forming method currently available for producing large numbers of complex-shaped parts cast to close tolerances in high-melting-point alloys. In this section, the advantages and limitations of investment casting are discussed in terms of costs: costs of improving the capabilities of the investment casting process itself (e.g., in taking care to assure close as-cast tolerances), and costs of alternative methods of production.

5.2.1 Dimensional Accuracy

One of the main advantages of investment casting is the ability to produce internal cavities and undercut features as integral parts of the mold. This avoids the process of core placement and maintains the advantage of the jointless mold. The two casting procedures having dimensional accuracy and surface finish comparable to investment casting are permanent mold casting and die casting, but both of these alternative casting methods entail the joining of two or more dies to make a mold, and the joint, or parting, between the die parts introduced an inherent inaccuracy because the thickness of the parting interface can only be controlled to a tolerance of several thousandths of an inch. Die casting and permanent mold casting are also limited by the melting points of the metals that can be cast - high-temperature alloys cannot be cast by these methods.

The high accuracy of investment castings is due to the smooth and inert mold surfaces and to the elimination of joints by the use of one-piece molds. The only alignment operation is that of the pattern die assembly, for which the metal components can be machined to fit with high precision. During pouring, ready flow in the preheated mold gives intricate detail and fine finish. The process thus offers a degree of precision unrivalled except in die casting.(3)

In investment casting, as in other metal shaping processes, attainable tolerances depend partly upon design. Tolerances are close ± 0.001 to ± 0.003 inch may be feasible on certain small dimensions, but it is widely accepted that values of ± 0.005 inch plus 0.5 percent of the dimension are more realistic for general application. As in other manufacturing processes, tolerances can be allotted on a functional basis, with maximum precision specified only for critical dimensions.(3)

Factors influencing the dimensional accuracy of investment casting are:(5)

(a) Shrinkage of the pattern material

(b) Shrinkage of the metal and direction of maximum shrinkage during solidification

(c) Shrinkage of the metal during cooling to room temperature (most measurements are made at room temperature)

(d) Expansion of the mold in preheating

(e) Expansion of the mold when molten metal is poured into it.

These factors are not additive because the shrinkages and expansions are not the same for all castings in all directions. The geometry of the individual castings, of the clustered castings and of the mold are difficult to compensate for analytically. Even if all the above listed shrinkages and expansions were known, overall shrinkage allowances can only be estimated, and finer tolerances (e.g., ± 0.002 in./in.) must be established through experimentation with the specific casting.(5,8)

To produce castings to the closest possible tolerances, it is necessary to consider the effects of pattern tooling, cross-sectional thickness of the pattern, location of pattern-die parting line, wax-injection conditions, temperature control of stored patterns, pattern assembly, molding, and cleaning and finishing of the casting. Since wax properties are the subject of this report, the wax injection consideration will be discussed here.(8)

The wax or plastic material must be consistent between runs and homogeneous within each pattern. Temperature and dwell time during injection must be accurately controlled. Deviations in these conditions can cause variations from the anticipated shrinkage. In particular, temperature variation should not be more than 2°F from an established optimum level.(5)

When pattern dies are held together by clamping force during injection, the injection pressure should not exceed the clamp pressure or the die will be forced partially open. In large-area patterns for turbine engine vanes, this may cause airfoil sections to be thicker than specified.

5.2.2 Surface Finish

In most applications, investment castings have the best surface finish of any casting process involving expendable molds. For the casting of high-temperature alloys, investment casting offers the best surface finish of any casting process. Tables 5.1 and 5.2 show comparisons of surface finish for several different casting procedures. (Shell molds, as listed in Tables 5.1 and 5.2, are not the same as investment shell molds; see Section 5.2.5.1 and Appendix A.)

Table 5.1

Approximate Ranges of Surface Roughness for Steel Castings Weighing up to 5 lbs., Made by Four Processes.*

Process	Micro-in. (rms)
Green sand mold	500 to 1000
Baked sand mold	250 to 500
Shell mold	125 to 250
Investment mold	60 to 125

Table 5.2

Typical Minimum and Maximum Roughness of Type 316 Stainless Steel Fittings Cast by Three Different Processes.*

Casting Process	Measured roughness, micro-in. (rms)		
	Minimum Value	Maximum Value	
		90% of Area	10% of Area
Sand	400	550	660
Shell	100	120	200
Investment	60	125	175

Measurements were made with a stylus-type tracer on all accessible areas; however, parting lines and other major discontinuities were not included in the traces. Before roughness was measured, all as-cast surfaces of the castings were blasted with zircon sand (7% larger than 100-mesh, the remainder smaller than 100-mesh but larger than 200-mesh).

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Surface conditions of the wax or plastic pattern, condition of the ceramic precoat, method of casting, the metal being cast, and the method of cleaning are the variables controlling surface finish. The method of casting affects the surface finish as a result of oxidation after pouring. Casting in inert atmospheres or in a vacuum provides smooth cast surfaces. In general, nonferrous castings are smoother than ferrous castings. Table 5.3 compares surface roughness of investment castings of five different metals.

5.2.3 Costs

Small intricate ferrous shapes are often most economically produced by investment casting. When investment castings costs for the production of a specific item exceed costs by other production methods, the reason is usually because there are a large number of operations in the process, especially operations involving operator skill. A detailed per-unit cost analysis of a typical investment cast part is shown on Table 5.4.

Costs may vary 50 percent or more among different investment casting procedures. The two examples that follow show cost differences between the use of ceramic shell and solid investment molds, arising from differences in pattern material (wax patterns in the ceramic shell molds, plastic for the solid molds), production rate and coring practice.

5.2.3.1 Cost Comparison: Ceramic Shell vs Solid Investment Processes*

Polystyrene patterns usually result in better surface finish than do wax patterns. However, because polystyrene has a higher coefficient of thermal expansion than wax, polystyrene patterns are used exclusively in solid investment molds while wax patterns can be used in both shell-type and solid-type molds (solid molds have the higher strength necessary to withstand the greater stresses generated during the removal of plastic patterns). Thus if high surface quality is desired in a casting, solid investment molds would likely be used with plastic patterns. The trend these days, however, is

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Table 5.3

Ranges of Surface Roughness of Investment Casting of Five Different Metals, as Measured in Two Different Plants*

Casting Alloy	Surface roughness, micro-in.	
	Plant A	Plant B
Aluminum	63 to 250	100 to 200
Magnesium	63 to 250	---
Copper	63 to 250	---
Steel	---	70 to 225
Stainless Steel	125 to 500	100 to 200

(Castings were made in solid investment molds produced from wax, plastic and mercury patterns. Data from plant A summarize experience with aircraft castings "as received" from foundries, and were taken by the visual-comparator method; areas of unusual roughness, such as corners and fillets, were not evaluated. Plant B measured roughness with a tracer instrument on about 50 different castings for each alloy shown, after the castings had been abrasive blasted or cleaned by tumbling.)

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Table 5.4
Cost Analysis of Typical Investment Casting

Item	Cost per casting	
Labor and Burden		
Cores (soluble-wax)	$0.84	
Core repair	0.07	
Pattern (wax)	0.74	
Chills (wax)	0.17	
Pattern repair	0.86	
Total pattern cost		$ 2.68
Sprue and riser (wax)	$0.18	
Gate-and-chill assembly	0.34	
Mechanical core supports	0.20	
Total gating cost		0.72
Molding (a)		1.30
Mold baking; wax removal	$0.70	
Melt and pour metal	1.85	
Total foundry cost		2.55
Pushout and vibrate	$0.20	
Waterblast (core removal)	0.12	
Cutoff	0.35	
Total cleaning cost		0.67
Grind	$0.30	
File	0.70	
Sand blast	0.25	
Total finishing cost		1.25
Visual inspection	$0.18	
Dimensional inspection	1.25	
Total, foundry inspection		1.43
Total cost, labor & burden		$10.60
Materials		
Soluble wax	$0.15	
Pattern wax	0.14	
Investment	0.75	
Metal	0.65	
Total materials cost		$ 1.69
Other Expenses		
Rejects (10% scrap)		$ 1.50
Heat treating (T6 temper)		0.20
Penetrant inspection		0.04
X-ray inspection (8 views)		0.87
Total Cost per Casting (b)		$14.90

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toward shell-type investment casting, because the investment process has been highly automated, furnace time for the molds is less (during burnout and preheating), dewaxing - or, in general, pattern removal - is faster and simpler, and the capital outlay for wax handling equipment is less than for plastic handling equipment (associated with block-type molds) which operates at higher temperatures and pressures.

The following example illustrates how, in this one instance at least, solid investment casting is more cost effective than shell investment casting. The example is based on data nearly 10 years old, and current methods of operation might give the opposite cost results, but the example is included here because the details of the cost difference are edifying:

The Hastelloy C investment casting shown in Table 5.5 was evaluated for production by both the ceramic shell process and the solid investment process. Wax patterns were used for the ceramic shell molds, and plastic patterns for the solid mold.

The cost of patterns (\$0.292 per casting for ceramic shell vs \$0.062 for solid investment) was a substantial contributor to the difference in cost. The difference in other costs was considerably less, percentagewise.

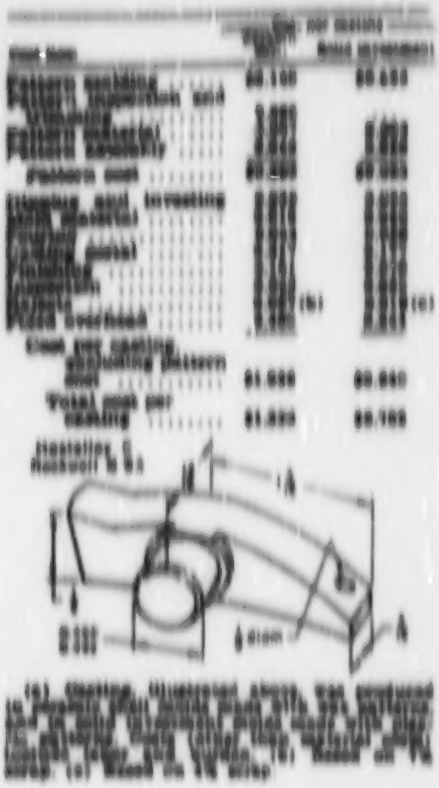
Cost details for production by the two processes are compared in Table 5.6. Production by the ceramic shell method cost almost twice as much as by the solid investment method. The solid mold process, therefore was selected.

As shown in Table 5.5 several factors accounted for the difference in cost. An explanation of the most important of these follows:

1. Pattern Molding. A total of 199 plastic patterns could be molded per hour, as opposed to 46 wax patterns per hour.
2. Pattern Assembly. Only 132 wax patterns could be assembled per hour, as opposed to 250 plastic patterns.

Table 5.5

Comparison of Costs for Producing Castings by the Ceramic Shell and Solid Investment Processes(a)*



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3. Pouring and casting metal cost more for the ceramic shell process, because the wax assembly required large runners for mechanical strength during processing of the clusters. In the ceramic shell, cluster weight was 16 lb. for 60 castings, as opposed to 14 lb. for 64 castings in the solid mold.
4. Finishing costs were higher for the ceramic shell process because of the cost of cleaning the residual refractory and the need to hold the 0.492/0.498-in. diameter within tolerance. The plastic patterns in the solid investment mold maintained this tolerance without secondary operations.
5. Inspection costs were higher for the ceramic shell process because of the need for 100-percent inspection on the 0.492/0.498-in. diameter. Statistical sampling sufficed for the solid investment mold.

5.2.3.2 Cost as a Function of Investment Casting Tolerance*

The assignment of tolerances closer than standard entails higher production costs and longer production times because closer tolerances increase both foundry time and the rejection rate. In some instances pattern dies may have to be made more than once, or the gating of acceptable dies may have to be improved. Table 5.6 shows how costs are influenced by tolerances.

5.2.4 Costs of Alternative Metal-Forming Processes

The value of investment casting is principally in the field of small complex components, and especially of components requiring refractory or high-melting-point metal composition. Since dimensional accuracy depends partly on the magnitude of the dimensions, the advantage over other casting processes diminishes with increasing size.(5) Most investment castings are below 10 pounds in weight, with the majority being less than 1 pound. Castings exceeding 100 pounds have been produced, however, with dimensions up to 18 inches.(3,8)

Despite the superlative technical capabilities of investment casting, its application has been restricted by the relatively high production

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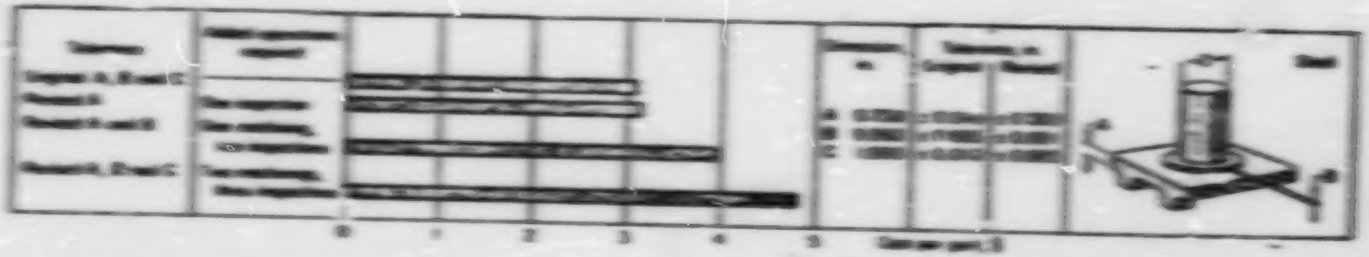
Table 5.6

Effect of the Tightening of Dimensional Tolerance on the Cost of a Part Produced from a Steel Investment Casting.*



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costs to those products for which an overall economy can be achieved by the elimination of machining, or for which there is no feasible alternative production method. A prime example is turbine blades; machining of such complex shapes on a mass production basis would be prohibitively expensive, and no other casting process can be used with such high-melting-point metals. Other examples are parts requiring accurate shaping in hard, wear resisting alloys that are inherently difficult to machine, or in alloys which are difficult or impossible to forge.(12) In such cases any alternative to investment casting may be more expensive when the overall cost of the finished component is used as the criterion.

The adoption of investment casting usually requires appreciable quantity production for amortization of die costs, although these are generally much lower than in die casting. The minimum practicable output varies widely according to the type of die, so that no general figures can be given. Die costs are also usually less than for forgings and sintered compacts, for which the hardest and least machinable die steels are required. For the mass production of large quantities of simple, low-tolerance parts, however, investment casting is not price competitive with forging and powder metallurgy because of their very low per-unit production costs.

Other applications of investment castings include impellers and other pump valve components in stainless steel and nonferrous alloys, waveguides, die inserts and parts for gun mechanisms. Milling cutters and other types of tools are also produced. Outside the engineering field, investment casting is used in dentistry, for surgical implants, and for jewelry and art casting. In some of these cases the expendable patterns are individually modelled rather than being produced by repetition from a die.(12)

5.2.4.1 Sand Casting vs Investment Casting*

The cost of investment casting is sometimes competitive with that of other casting methods especially when machining operations are eliminated by the use of the investment process. Investment casting also competes with forging and with machining from bar stock. The three examples that follow compare costs of investment castings with costs of making the same part by alternative methods.

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When the part shown in Table 5.7 was produced as a sand casting, the internal oil slot was milled in with a slotting cutter and the hole leading to it was drilled. Producing the part as an investment casting permitted the slot to be cored, and it did not require machining. Casting and machining costs for the sand and investment castings are compared in Table 5.7. Savings in the machining costs were possible because of the superior dimensional accuracy attainable when the part was made as an investment casting. The three concave reliefs required no machining when made by investment casting, and only one-third as much stock removal was needed on all other machined surfaces.

5.2.4.2 One-Piece Investment Casting vs Welded Assemblies*

A diffuser strut for an aircraft engine was originally designed to be made of two forged halves, which were machined on mating surfaces and then welded together. Alternative designs required that the feet of the part be forged or cast, that the vane be formed from sheet metal, and that the feet be welded on. All welding was done by the gas tungsten-arc method.

The strut was later produced as a one-piece investment casting by the ceramic shell process. Producing the struts as castings reduced the cost by $82 per strut, which represented a reduction of approximately 75 percent, including machining costs.

5.2.4.3 Investment Casting vs Machining from Bar Stock*

Two sets of fixtures (one piece from each is shown in Figure 5.3) used in the high-temperature brazing of stainless steel tubing were originally made of Hastelloy X by machining from bar stock. The cost of set A was $58.00, and that of set B was $40.25.

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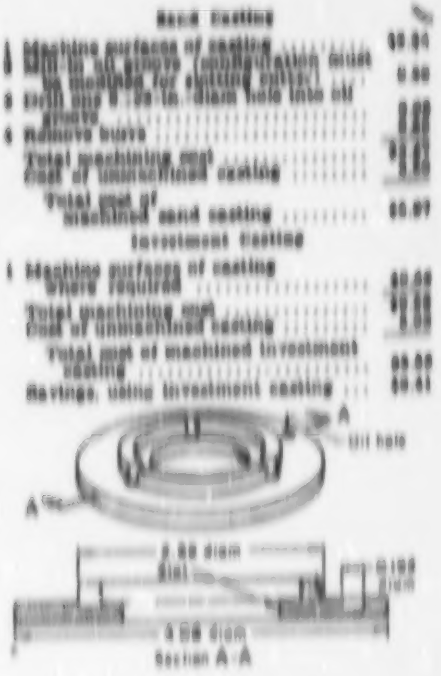
Table 5.7

Machined Sand Casting vs Machined Investment Casting*


A
A
Drill hole
Section A-A

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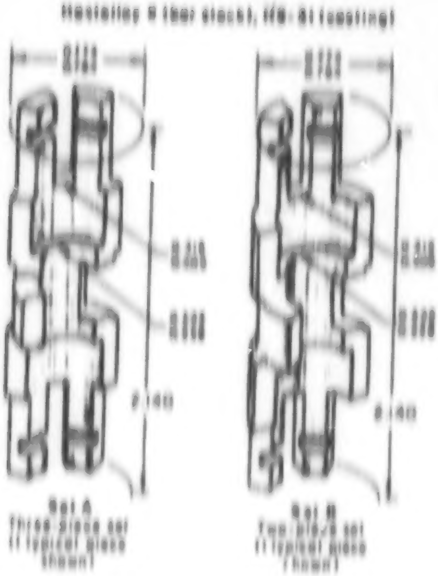

Figure 5.3

Typical Pieces for Two Brazing Fixtures that were Made at Less Cost by Investment Casting than by Machining from Bar Stock*

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The same fixtures were later made of HS-31 (an acceptable alternative material) by the ceramic shell investment casting process, at a cost of $4.47 for set A and $2.56 for set B. The investment cast fixtures also had a longer service life.

5.2.5 Discussion of Alternative Metal-Forming Methods to Investment Casting

The implications of the available tolerances and surface finish are that while loose fits are attainable between as-cast components, machining or grinding allowances are normally necessary for bearing surfaces, precision threads and other close-tolerance needs.(3)

The minimum metal thickness that can be satisfactorily run depends partly on the area of the section being cast. Although thicknesses of 0.010 to 0.015 inch have been obtained over very short distances, 0.020 inch is the practical minimum for appreciable areas - on the order of 1 square inch - and 0.060 inch is the practical minimum for larger areas. The minimum diameter for cast holes is also on the order of 0.060 inch.(3)

The general design capability of investment casting is high, with few shape restrictions. Mold joint considerations are absent and components can be produced without draft taper. Using the wide range of techniques available to the investment caster, virtually any shape can be formed.

Apart from dimensional errors, investment castings are subject to a similar range of defects to those encountered in other processes - e.g., misrun (i.e., incomplete filling of the mold cavity) and non-metallic inclusions. Defects with causes peculiar to investment casting include blowholes due to incomplete removal of wax residues and surface defects resulting from local failure of the primary coating.

In the cost examples given above, investment casting was compared to sand casting, welding, and machining, as alternative methods of manufacture. It is obvious from these examples that investment casting is more cost effective, principally because of the relative simplicity of investment casting and the minimal need for finishing operations and machining. There are other methods having more similarities to investment casting - namely, die casting, permanent mold casting, shell molding, and powder metallurgy. Appendix A contains detailed summaries of these alternative processes, but their advantages and disadvantages relative to investment casting are given here.

5.2.5.1 Shell Molding(8)

Aggregate molding is a term referring to traditional sand casting, to shell molding, and even to investment casting. In each casting method the mold material is aggregated refractory material; in virtually all other respects the processes are entirely different from one another.

Shell molding is a casting method in which fine sand (on the order of 100 to 150 mesh) is mixed with about 5 percent of a suitable synthetic resin, such as phenol formaldehyde. Metal pattern plates (which are permanent patterns - as opposed to the disposable patterns used in investment casting) are heated to between 400 and 500°F. (The two pattern plates correspond to the two halves of the shell mold to be produced.) They are sprayed with a silicone release agent. The hot patterns - one at a time - are fastened to a "dump box" containing the sand/resin mixture, with the pattern surface facing the opening of the dump box. When the dump box is inverted, the sand/resin mixture falls on the hot pattern surface. The heat penetrates the mixture and softens the resin causing it to bind the sand together. After 8 to 20 seconds, depending on the desired shell thickness, the dump box is re-inverted and the loose sand/resin mixture falls away from the pattern plate. Additional curing of the resin is affected by further heating of the shell and pattern assembly, then the shell is stripped from the pattern plate. The complete shell mold consists of two such shells fastened together sufficiently to withstand the hydrostatic forces of the poured metal.

Shell molding produces surface finishes on the order of 125 microinches, rms; tolerances of ±0.003 inch/inch are attainable, with dimensions across the parting line being within ±0.010 inch. Such tolerances are not as close as those attainable with investment casting, but as with investment casting shell molding is amenable to the casting of almost any metal. Casting sizes are typically on the order of that of automobile crankshafts, which are produced by this method. The major disadvantage of shell molding relative to investment casting is the level of complexity that can be achieved in the castings - the nature of the method of shell mold manufacture necessitates that in order for the shell molds to be removed from the pattern plates, there must be no under cuts in the cast design, and allowances must be made for draft so that the molds can be removed from the pattern plates without breakage.

5.2.5.2 Die Casting(3,12,13)

In die casting (called pressure die casting in England and Europe) metal is injected under pressure and at high velocity into a permanent mold where it solidifies under externally applied pressure. The result is a casting having good surface quality and good dimensional tolerance - except for across the parting line of the dies.

Recent years have seen the rapid growth of die casting in aluminum alloys, particularly the very fluid silicon containing alloys. The size of castings has also rapidly increased following the introduction of heavier casting machines. Smaller but significant quantities of castings are produced in magnesium alloys, in fusible alloys based on lead and tin, and in copper alloys, especially 60/40 brass. Application of the process to alloys of higher melting point is under development and not currently operational. Thus it is not suited to the casting of high-temperature alloys, as is investment casting.

5.2.5.3 Permanent Mold Casting(3,12,14)

Permanent mold casting (which in England and Europe is referred to as gravity die casting) is notable for the very large output of castings in aluminum alloys, for which the process is predominant as a mass production technique. There is also a substantial production of copper alloys and cast iron, particularly in relatively simple shapes, and a limited output of magnesium alloys. The process is only suitable for fluid alloys owing to the high freezing rates obtained in the permanent metal molds.

Except for the method of feeding the molten metal into the two-part, hinged molds (sometimes additional mold parts called slides are used for the permanent mold casting of more complex shapes) permanent mold casting is practically the same as die casting, though generally larger castings are made in the permanent mold process.

Permanent mold casting produces castings having good surface finish; but the existence of the parting surface in the molds does not allow the close dimensional tolerances common to investment casting, and the fact that the mold halves must be opened after casting restricts the level of complexity of the shapes being cast. Permanent mold casting is also not amenable to the casting of the high temperature alloys.

5.2.5.4 Powder Metallurgy (P/M)(1,18)

Of the four alternative metal forming methods discussed here only powder metallurgy shares with investment casting the capability of forming shapes out of high-temperature materials. In fact, P/M can be used to manufacture parts out of uncastable materials such as tungsten, as well as combinations of metals and ceramics.

The process of P/M consists of compressing metal powders, or combinations of metal powders and powders of other materials, in a suitably shaped mold. After initial pressing, the parts are heated in an oven to a temperature close to the fusion point of the metal components (sintering), then repressed if necessary, or otherwise finished with machining, plating, or whatever.

One disadvantage of P/M is the intrinsic porosity of the parts produced. (In many respects this porosity is an advantage, such as when the parts are to be impregnated with lubricants.) In finishing operations such as plating and anodizing, corrosive chemicals invade the surface of the porous parts and are difficult to remove. A further disadvantage of P/M is the relative simplicity of the parts that can be produced - undercut surfaces are difficult if not impossible to produce in direct P/M processes and require subsequent machining.

5.2.6 Disadvantages of Investment Casting

In addition to the environmental hazard associated with the volatilization of wax additives and fillers during the mold preparation procedures, investment casting is labor intensive, and the size of castings is limited (the weight of wax or plastic required for a casting increases as the cube of the characteristic linear dimensions of the casting).(3) The majority of investment castings weigh less than 1 pound.

5.3 Size of Investment Casting Industry

The Investment Casting Institute places the number of investment casting foundries in the United States at about 150.(2) Uncertainty as to the exact number derives from the fact that not all investment casting foundries are members of the ICI. And, of course, there are many many types of business operations where investment casting is carried out as a nonspecialty - e.g., there are probably thousands of jewelry manufacturers practicing investment casting to some extent, and there are probably many foundries specializing in other types of casting with investment casting as a small sideline.

5.3.1 Employment and Value of Shipments

Census Bureau data on foundries includes a listing of steel investment foundries and a listing on nonferrous foundries not elsewhere classified which includes nonferrous investment foundries.(16) In Table 5.8 below, showing the value of shipments from investment casting foundries, the figures for nonferrous investment castings were derived on the basis of data from the Investment Casting Institute - namely, that the ratio of dollar value of ferrous to nonferrous investment castings is 3 to 1; that is, 75 percent of the value of investment cast shipments are ferrous castings, and the remainder are nonferrous. (The ICI has also made a rough estimate that the ratio of the number of ferrous castings to nonferrous castings is on the order of 80/20 to 90/10;(2) the difference between these estimated ratios and the ratio of values of ferrous to nonferrous castings probably results from the consideration that nonferrous investment castings are more likely specialty items for which the per-unit cost is slightly higher because of smaller number of castings.) Thus it can be assumed the dollar value of nonferrous investment castings is one-third of the dollar value of ferrous investment castings. Employment figures in Table 5.8 are also from Census Bureau data, except that the employment in nonferrous investment casting production is also derived on the same basis as above - that is, for each three people employed in ferrous investment casting, one is employed in nonferrous investment casting.

According to the Investment Casting Institute the "adjusted net sales" in the investment casting industry in 1975 were $230 million.(2) The difference between the $230 million for 1975 and the $544 million shown in Table 5.8 might be attributed to several factors:

1. The ICI figure for 1975 might not take into account the value of castings produced for in-house operations - e.g., one jet engine manufacturing company produces its own investment cast turbine blade and vanes, and these may not be included in the ICI data.
2. Not all investment casting foundries are members of the ICI, and their "adjusted net sales" might not be included in the $230 million estimate.
3. One information source - the publisher of a manufacturing trade journal - said he thought the ICI estimates money value and production volumes were probably on the low side and are "likely based on educated guesses", since the investment casting industry is not as communicative within itself as are other manufacturing industries.
4. The difference between the ICI's definition of "adjusted net sales" and the Census Bureau's "Value of Shipments" might account for a large part of the difference.(17)

Table 5.8

Employment and Value of Shipments for the Investment Casting Industry (Note: Data for ferrous castings is from Census Bureau sources; nonferrous employment and shipment value are taken as being one-third of the ferrous numbers).

Value of Shipments (millions of dollars)				
Ferrous Castings	$167.6	237.7		408.0
Nonferrous	55.8	79.2		136.0
Total	$223.4	316.9		544.0
Employment				
Ferrous			11,600	13,900
Nonferrous			3,867	4,633
Total			15,467	18,533

According to the ICI, the volume and dollar value of investment castings can be broken down between "general engineering castings" and "gas turbine blades and vanes" as follows:(2)

Weight basis:

general engineering castings	75%
gas turbine blades and vanes	25%

Dollar basis:

general engineering castings	50 to 55%
gas turbine blades and vanes	45 to 50%

The extra dollar value (per unit of weight of cast metal) of gas turbine blades and vanes probably derives from the greater degree of care needed in the casting of these parts which in service are exposed to extreme mechanical and thermal stresses. Turbine components are cast in alloys of precise composition, and they are cast in vacuum and in inert atmospheres to reduce oxidation during pouring and solidification; extremely close tolerances are probably also important, which means a high reject rate.

5.3.2 Growth of the Investment Casting Industry

According to the Investment Casting Institute,(2) investment casting is growing and taking business from other techniques of manufacturing such as forging, powder metallurgy, and especially from machining. Sewing machine parts (for which production volumes are in terms of hundreds of thousands of parts per year) and golf club heads are examples of products which used to be produced by other methods but which are now produced by investment casting. For both sewing machine parts and golf club heads, investment casting offers the potential for greater intricacy of design, greater manufacturing accuracy, and it allows the designer a wide range of alloy types. The ICI spokesman says that practically any alloy - aluminum, magnesium, steel, cobalt, super alloys, beryllium copper, copper, titanium - can be more economically cast by investment casting except for lead, zinc and similar metals. Investment casting can typically save 50 percent on overall manufacturing costs because the finishing operations are so minimal; even die casting entails more finishing operations, has less intrinsic accuracy (due to parting line in the die), and has less potential for design intricacy. With investment cast components, finishing operations may consist simply of electropolishing and plating, with no machining other than the grinding away of the gate lug.

Growth rate of the industry is presently near zero, but the figures for 1976 are expected to show a slight gain in profits. A bad year was 1975, but for the most part investment casting foundries have not had to lay off personnel. The current slow growth is credited to the general recession.(2)

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6.0 INVESTMENT CASTING WAXES

The proceeding section dealt with the investment casting industry, its size, its manufacturing capabilities and its limitations. This section deals with the wax used in investment casting, the wax that is lost in the lost-wax process, which is the older name of investment casting.

There are actually many types of wax that have been used in the lost-wax process. In the earliest times, the waxes used obviously must have been of some natural type, probably most commonly beeswax or some kind of vegetable wax. Modern waxes are compositions of natural and synthetic components which can, in general, be referred to as thermoplastic materials.(1) Thermoplastic materials in this context refers to natural and synthetic waxes as well as to such unwaxy materials as polystyrene, which has been used widely in investment casting for several decades both by itself and as a filler material within the more traditional wax compositions. The term thermoplastic, as applied to both waxes and polystyrene (as well as to other materials discussed below), indicate that these materials soften and liquify when heated, but regain their room temperature properties when cooled. Polychlorinated biphenyls have been used as fillers in these modern waxes. Polychlorinated *poly*phenyls, often contaminated with PCBs, have also been used because they perform well as components and fillers in investment casting waxes - that is, polychlorinated polyphenyls improve significantly the desirable properties of casting wax formulations.

It should be noted that PCBs *per se* are no longer used in investment casting. The only chlorinated biphenyl that was used was the fully-chlorinated decachlorobiphenyl, and it was used only during a period of several years ending in the middle of 1976.(2) Polychlorinated *ter*phenyl, on the other hand, has been in use as a wax component for more than 20 years and continues to be used now.(3) To the extent that polychlorinated terphenyl (PCT) contains PCB contamination, PCBs are still an issue in investment casting.

6.1 Background

When lost-wax process was first practiced several thousand years ago, practically any wax would suffice as a pattern material for wax expansion on heating and shrinkage on freezing had little effect on the usefulness of the casting as close tolerances were not required. Archeological evidence indicates that most of the earliest lost-wax castings were of ornamental and artistic significance. Also, the wax pattern was more than likely shaped or carved by hand and at low temperature prior to the making of the mold, so that the investment caster achieved a casting that was an accurate representation of his pattern. The main defects were likely to have been misrun castings (i.e., incompletely filled molds), rough surface finish (the mold material would probably have been bonded sand of a course grade by today's standards), and nonmetallic inclusions in the casting (arising from impurities in the melted metal to be poured, or from impurities in the wax which might not have been entirely removed from the mold when the wax pattern itself was melted and poured out).(4)

The only investment casting operations for which patterns are presently handmade at or near room temperature are in jewelry and dental work and in limited-edition ornamental or artistic castings. Most investment casting, however, is done on a mass-production basis. Because such mass-produced parts are often components in products of commercial or strategic value, close tolerances and close dimensional similarities between the castings are very important, which means that the patterns from which the molds are made must also fall within certain design tolerances and must all be closely similar to one another. It is in this mass production of thermoplastic patterns that wax properties became critical, especially the property of thermally-induced expansion - that is, the coefficient of thermal expansion, and the expansion (or contraction) that takes place during melting (or solidifying). Since the patterns are themselves mass produced in die-type molds, dimensional allowance (as discussed in the previous section) must be made for the shrinkage of the pattern wax during solidification in the pattern die, as well as for the further shrinkage that takes place as the pattern cools to room temperature.

Expansion of the wax during dewaxing of the investment mold is also a problem. Within the last 5 years investment shell molds have become the type most commonly used because this type of investment casting has become so automated.(5) Shell investment molds are more fragile than the solid type, which means that too much expansion of the wax during the process of pattern removal, can cause the shell investment mold to fracture.

Since the Second World War, when investment casting became popular as a method of producing precision castings of high-melting-point alloys, considerable effort has been paid to this problem of the dimensional changes of wax as a function of temperature. Among the pattern materials used in the past several decades with great success are tin and mercury. Both give high surface quality in the product castings, better finishes than can be obtained using the best of today's waxes, and both materials are less subject to dimensional changes as a function of temperature than are waxes. However, the problems of toxicity and special handling outweigh the benefits. With tin as a pattern material, high-temperature equipment was needed for the injection of molten tin into the pattern dies, which themselves had to be made of materials that could withstand the stresses of continual heating and cooling cycles. Machinery and dies capable of withstanding temperatures exceeding the melting point of tin cost more than do machines capable of working at wax-melting temperatures, usually below 200°F. With mercury as a pattern material, the problem was one of cold handling; the mercury pattern, once cast in the pattern die, had to be maintained at low temperature (below -70°F for the pattern dies, and below -37°F for the rest of the process until meltout). Removal of the mercury remaining after meltout was achieved by treatment of the mold with successive solutions of nitric acid and sodium hydroxide and acetone, all of which result in considerable process complexity. Mercury toxicity was also a problem.(6)

Modern wax formulations allow the mold-making process to take place at maximum temperatures below about 200°F, with minimum temperatures being whatever is comfortable for the people making and assembling the patterns.

Operating temperatures for pure polystyrene patterns are slightly higher, except during pattern removal when the pattern is usually burned rather than melted out of the mold.

6.2 Desirable Wax Properties

The expansion of a typical parrafin wax from 60°F to its melting point is about 14 percent. Such a wax is usually too soft at an elevated temperature, e.g., 100 to 110°F, to be used in investment casting. The ideal wax would undergo no volume change as it was heated through its melting point. Also, the ideal wax would remain hard at elevated temperatures that are less than the wax's melting point.(7)

There are other properties of an investment casting wax besides high-temperature hardness and thermal expansion that are important, such as the viscosity of the molten wax, which may change after more than one use; and, in those investment casting operations where solvents are used to remove the pattern from the mold, wax solubility is a consideration. Wetability is a consideration too, as the investment slurry must be able to wet the wax surface and adhere to it well enough to ensure a good surface on the product castings. The following wax properties are also important:(6)

- Accurate Surface Finish - The pattern should reproduce the internal surface details of the pattern die because such detail is ultimately carried to the final metal casting.
- Minimal Ash Content - After the wax is melted out of the ceramic mold, the mold is heated to a high temperature in order to vaporize and melt out the remaining wax absorbed in the ceramic mold structure; any ash or unburned carbon remaining in the mold can affect the surface qualities and metallurgical properties of the finished casting.

- Narrow Solidification Temperature Range - In order to reduce the amount of time required to make an investment casting, the speed at which the pattern can harden in its die must be minimal; if the wax is injected into the pattern die at a temperature very close to its melting point, the wax will harden rapidly so the pattern can be removed quickly.
- Strength - At room temperature, investment casting waxes should, if stressed mechanically, break before they will bend plastically; this is not a property of ordinary waxes.
- Narrow Ductile-to-Brittle Transition Range - Upon cooling, the faster the wax pattern becomes brittle and loses its ductility, the sooner (and at higher temperature) the pattern can be removed from the pattern mold without the pattern sagging or otherwise being deformed by handling.
- Resistance to Gum Formation - Some waxes are likely to oxidise in the machine that injects the wax into the pattern mold; the result is wax-insoluble gums that interfere with the injection process.

6.3 Filled and Unfilled Waxes

It is common practice to use finely divided solid filler materials in the pattern wax in order to reduce the cooling shrinkage of the wax patterns. However, fillers tend to separate from the melted wax due to differences in density between the wax and the filler material, and they tend to increase the viscosity of the melted composition. Also, some filler materials have undesirable thermal expansion characteristics, and some have undesirable low melting points.(9)

Various fillers or extenders have been added to base waxes in an effort to inhibit or prevent shrinkage. Compositions formed by such additions have not possessed the required non-shrinkage property, and frequently possess other undesirable characteristics too. Inorganic fillers such as powdered mica or silica are left in the mold in small amounts subsequent to melting and removal of the wax pattern material. Irregularly shaped particles, such as wood fiber, sugar or silica, inhibit the flow - i.e., increase the viscosity - of the melted wax. Various plastic additives and sugar have a higher specific gravity than pattern wax and settle out either during the pre-casting operation or during casting, at which time particles of the additive settle into depressions within the mold. Polystyrene beads have also been used as fillers but have disadvantages: the pattern wax melts first and runs out of the mold, leaving a polystyrene residue; if heating rates are not properly controlled, the polystyrene will char, making it difficult to remove from the mold. In addition, even if the polystyrene is melted properly, its viscous or tacky consistency often causes it to pull away some of the refractory composition from the wall of the mold, thus causing defects in the final casting.(9)

The difference between wax fillers and wax components is that fillers are solid materials, usually in a powder form or in the form of small beads, and they have a melting point that exceeds that of the rest of the wax composition; components, on the other hand, can be and probably usually are, miscible in the wax matrix and melt with it.

8.3.1 PCBs and PCTs in Waxes

For a period of several years ending in the middle of 1976, decachlorobiphenyl was used as a filler in investment casting waxes. As far as can be determined, decachlorobiphenyl is the only PCB that has been used in investment casting waxes, except for those PCBs which enter the waxes as impurities in other chlorinated polyphenyls used as wax components or fillers. No PCBs are currently being purposefully added to investment casting waxes. PCBs constituted between 5 and 70 percent of the total casting wax formulation, according to the patent covering its use in waxes,(1) though actual commercial compositions of PCB wax contained on the order of 25 to 50 percent of the decachlorobiphenyl.(10)

Polychlorinated terphenyls are added to waxes to the extent of about 30 percent(2) to 40 percent(3) of the total wax weight, with the range being from 30 to 60 percent.(10) PCTs make up the resinous component, or a portion of the resinous component of the wax formulation. Terphenyls make the wax harder at all temperatures below the melting point, they cause the wax to harden faster by improving the thermal conductivity, and they reduce the coefficient of thermal expansion of the wax, though not to the extent that decachlorobiphenyl does.

6.1.1.1 Decachlorobiphenyl: History and Advantages

A patent for the use of decachlorobiphenyl was applied for in October of 1972.(1) In September of 1971 an application for patent was filled by the same inventor on the use of cyanuric acid as a wax filler.(11) Comparison of these two patents gives an insight into the purpose of fillers in waxes, and shows the relative value of cyanuric-acid-filled wax, decachlorobiphenyl-filled wax and unfilled wax. The following material comes directly from these two patents:

"The composition of this invention comprises a thermoplastic pattern material and decachlorobiphenyl in an amount of from 5 percent to about 70 percent by weight of the total thermoplastic pattern forming composition. For high quality castings, the particle should not exceed 100 mesh. Decachlorobiphenyl does not appreciably expand or shrink in a range from ambient room temperature to a temperature of 105°C. In pattern forming compositions decachlorobiphenyl is inert, hence it is not subject to shrinking upon cooling as are the lower melting thermoplastic portions of the thermoplastic pattern forming compositions."(1)

In his patent on the cyanuric acid filler, the inventor says virtually the same, except that the material is stable to its sublimation temperature which is about 330°C.(11)

The following table lists the physical properties of decachlorobiphenyl and cyanuric acid:(1,11)

	Decachloro-biphenyl	Cyanuric Acid
Molecular weight	499	129.08
Chlorine content	71.7%	0
Specific gravity	1.95	1.73
Melting point	305.0 to 305.5°C	330°C (sublimates)
Boiling point (at 760 mm Hg)	450 to 460°C	--
Dielectric constant	3	
Coefficient of thermal expansion per °C	52 to 63 x 10^{-6}	

In both of these patents, the inventor defines a basic pattern wax of the following composition, then compares the thermal expansion characteristics of this wax to the same wax with 60 percent cyanuric acid in one case and 60 percent decachlorobiphenyl in the other case. The basic wax is:*

	Parts by Volume
Terpene polymer (115°C m.p.)	55
Synthetic paraffinic mineral wax (200°C m.p.)	5
Paraffin (138 to 140°C m.p.)	20
Natural carnauba wax	10
Microcrystalline wax (175 to 180°C m.p.)	10
	100

In each of the cases where decachlorobiphenyl and cyanuric acid are added to the above wax formulation, the fillers (i.e., the cyanuric acid and the decachlorobiphenyl) retained their particulate identities. The following table compares the thermal expansion characteristics of the above wax with and without these two fillers:

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*Appendix B is a glossary of names of different types of casting waxes and wax components.

Temp. (°F)	Unfilled Wax	Wax with Cyanuric Acid	Wax with Decachlorobiphenyl
75	0%	0%	0%
85	0.35	0.0	0.0
95	1.06	0.21	0.42
105	1.41	0.45	0.42
115	2.64	1.07	1.25
125	4.05	1.71	1.25
135	5.63	2.14	1.66
145	6.69	2.35	2.47
155	7.57	2.56	2.47
165	8.80	2.99	3.25
175	8.98	3.21	3.25

In spite of the incremental steps shown for the deca-filled wax, the method of measurement is supposed to have been within ±0.2 percent accurate. For all practical purposes, the cyanuric acid has the same thermal expansion properties as the deca-filled wax.

Decachlorobiphenyl was used as a wax filler by only one manufacturer and for a period of only several years (1973-1976). To summarize its advantages: At the initiation of its use in investment casting wax it was a low-cost filler that performed well in controlling the thermal expansion of the wax, and, during the firing of the investment mold, it burned out cleanly leaving virtually zero ash and residue to contaminate the cast metal.

The use of decachlorobiphenyl was discontinued in the middle of 1976. The reasons for the discontinuance were (1) controversy over the use of PCB and the potential for adverse publicity for the wax producer using the PCB in its product, (2) impending legislation on both the state and Federal levels which would ban the use of PCBs, (3) the increasing cost of decachlorobiphenyl, which had to be imported because it was never manufactured in the United States.[12]

5.2.1.2 Polychlorinated Terphenyl: History and Advantages

Polychlorinated terphenyls have been used in investment casting waxes for more than 20 years, and are still incorporated into waxes by at least three of the eleven known wax manufacturers. PCT is not a wax filler, as it is miscible with and melts with the total wax formulation. In effect, PCTs constitute the resin component of the wax formulation. (Resins have been used in investment casting waxes for at least as long as PCTs, and likely longer; resin is defined in Appendix B, which is a glossary of components, fillers and additives used in waxes.) There are no patents covering the use of PCTs in waxes used in investment casting, but there is a patent claiming the use of a specified proportion of PCT in waxes used as tooling compound (see Section 4.0).

PCTs are incorporated into investment casting waxes in amounts ranging from 30 to 40 percent, with the average being on the order of 40 percent. The function of the terphenyls in waxes is generally the same as that of the decachlorinated biphenyl: it improves the working properties of the wax. Specifically, terphenyl reduces the change in wax volume as a function of temperature and during solidification (and melting), and it hastens solidification, probably by improving the conductive heat transfer properties. According to one data source, terphenyls cause the wax to rapidly form a shell in the pattern mold which allows quick removal of the pattern from the mold,[3] but it seems more likely this characteristic is a result of improved heat transfer although the terphenyl may also increase the hardness of the solidified wax, the wax still has a volume shrinkage upon cooling which would result in excessive stresses on a thin shell of solidified wax. It therefore seems likely that terphenyls cause the wax to harden faster, and to a greater hardness; the overall result being the achievement of rapid production of high quality patterns.

Prior to 1972, polychlorinated terphenyl was available from Monsanto. Terphenyl cost at that time was about 30¢/lb. In April of 1972 terphenyl production was ended in the United States, and wax manufacturers had to start importing it. Prices of imported terphenyl were 20¢ to 40¢/lb higher than for the domestically-produced material; the current price is about 70¢/lb.(2,3) Assuming that terphenyl investment waxes are 40 percent terphenyl, the cost increase in the wax product has been nearly 30¢/lb since the time when domestic production of terphenyl ended.(3)

6.3.1.3 Current PCB/PCT Use and Current and Impending Legislation

PCBs are no longer intentionally used in the investment casting industry. The only PCBs that are in currently-produced waxes are in the form of contamination in the PCTs used in waxes,(however, the sole U.S. distributor of PCTs is currently certifying that their PCTs contain less than 0.05% PCBs).

PCT waxes are used widely in investment casting, but not exclusively. That is, not all investment casting foundries use terphenyl waxes. Two of the three manufacturers of PCT waxes have stated that sales of these waxes constitute less than 50 percent of their total volume of wax sales, the implication being, by one manufacturer, that sales were purposely being held at this level, possibly because of impending legislation that would severely restrict or ban the use of PCTs as well as PCBs.(2,3) Table 6.1 is a summary of current and impending state legislation concerning PCBs and PCTs.

6.3.2 Disadvantages of PCB/PCT Waxes

There are two areas of disadvantage associated with chlorinated polyphenyl investment casting waxes: industrial and environmental. The main industrial problem associated with the previously-used decachlorobiphenyl waxes was the same problem that is associated with any filled wax formulation - namely, the difference between the specific gravities of the

Table 6.1

Status of State Legislation Restricting Manufacturing,
Use and Sale of PCBs and PCT Compounds

State	Status of Legislation	Description of Legislation
Illinois	Proposed; passed Senate and may be voted on in 1977 in House	PCB compounds or mixtures; does not include PCTs
Indiana	Law	Includes both PCBs and PCTs
Michigan	Law	Includes both PCBs and PCTs
Minnesota	Law	Includes only PCT compounds
New York	Proposed; two bills are in committee	Includes only PCBs
Ohio	Very little activity; may be a year before legislation is proposed	
Wisconsin	Law	Includes only PCBs

wax and the filler material, which means that the melted wax must be continually aggitated prior to injection (into the pattern die) so that the filler material does not settle out (or rise to the top, if the specific gravity of the filler is less than that of the wax). This difference in specific gravities might be one reason why, in some investment casting foundries, the wax is injected into the pattern die in a semi-molten state, or even in a soft, but solid, state. (Another reason for such low-temperature injection is to minimize the cooling shrinkage of the pattern after it has been injected into the die.) A second industrial disadvantage of decachlorobiphenyl-filled waxes was a trivial one: The product wax was still not ideal in its properties. This was not really a problem, of course, because the performance of decachlorobiphenyl waxes was apparently very satisfactory.

It is the environmental problems caused by PCBs that have condemned both PCBs and PCTs in investment casting. Polychlorinated polyphenyls endure in the environment, and, though these chemicals are not acutely toxic and though there is little data on their chronic toxicity, evidence has been found indicating a considerable potential for environmental damage which can both directly and indirectly influence human beings. Such evidence of the influence of chlorinated hydrocarbons on the life cycles of fish and birds has been sufficiently covered elsewhere and need not be reiterated here. Interested readers are referred to Renate Kimbrough's definitive article, "The Toxicity of Polychlorinated Polycyclic Compounds and Related Chemicals", published in the January, 1974 issue of CRC Critical Reviews in Toxicology. There are more than 100 references cited in the bibliography.

6.1.2.1 Environmental Stability of Decachlorobiphenyl and Polychlorinated Terphenyl

It has been argued by persons both in the investment casting industry and outside of it that decachlorobiphenyl, by virtue of its extreme stability (melting point: 480°F; boiling point: 890°F), is in actuality an environmentally safe material. The flaw in this argument, however, is that if it is so stable, and, indeed it is the most stable of the polychlorinated biphenyls, it will accumulate in the environment more than would other members of the chlorinated biphenyl family and thereby have an effect over long periods which might exceed that of the less chlorinated members of the family. In other words, though the water solubility and vapor pressure of decachlorobiphenyl may be less than that of any other chlorinated biphenyl, if there is more decachlorobiphenyl in the environment than other chlorinated biphenyls, then it could have an effect on the environment out of proportion to its relative inertness. Data on the environment endurance and degradation pathways of decachlorobiphenyl and of each mixture and pure species of chlorinated biphenyls is scarce. Among the few things known for certain aside from the potential for, and reality of, environmental hazard - is that the higher chlorinated forms endure longer than the lower chlorinated forms. But whatever the level of chlorination, PCBs in general can be accumulated in biological systems so that concentrated amounts of these materials can be passed up the food chain.

With respect to chlorinated terphenyls, very little is known about either the toxicology or the environment endurance. In a study by Allen, (13) commercial PCTs manufactured by Monsanto were fed to rhesus monkeys in concentrations of 5000 ppm for three months. Physiological changes, including morbidy, resulted. Subsequent testing by Versar Inc., of the terphenyl formulation used by Allen indicated, however, that it was contaminated with PCB to the extent of 0.56 percent, (14) sufficient concentration, according to Allen, to account for the large portion of the damage noted in the test animals. (15) Thus little is known about terphenyl toxicology since so little study has been done, and that work which has been done was likely influenced by PCB contamination of the PCTs tested.

As for environmental endurance, PCTs, like PCBs, are stable in direct relation to the degree of chlorination.

6.1.2.2 Sources of PCB/PCT Loss to the Environment in the Investment Casting Industry

The decachlorobiphenyl used in investment casting waxes until the middle of 1976 was a very high melting, low volatility material in comparison to the polychlorinated terphenyl formulations still being added to some casting waxes. It is likely that any chlorinated biphenyl contamination in the PCTs currently used is on the average not fully chlorinated, which means such PCB contaminant would be more volatile than the previously-used decachlorobiphenyl. Thus it is likely that on a pound-for-pound basis more terphenyl and its contaminant biphenyls could be lost by volatilization during the high temperature portions of the investment casting foundry process than was the case with the deca PCB. Figure 6.1 is a flow chart of wax usage in a typical investment casting foundry. Figure 6.2 shows an idealized flow chart of an investment foundry and the probable points of PCB/PCT entry into the environment. The highest temperature part of the process shown in Figure 6.2 is the mold firing and preheating phase where the molds are heated to as high as 2000°F, and any residual wax remaining prior to firing is volatilized into the atmosphere in this part of the process. (The amount of wax remaining in the molds prior to firing is in the range of 0.1 to 10 percent.) PCB fillers and PCT additives constitute an average of about 40 percent of the wax.

Losses to the atmosphere from the dewaxing process are significantly less than from the firing process because most foundries use autoclave dewaxing which, during operation, is isolated from the air. Opening of the autoclave might have contributed to release of decachlorobiphenyl to the atmosphere, but probably only slightly since the autoclave process does not reach sufficient temperature to even melt decachlorobiphenyl (m.p. 580°F). The less chlorinated, lower-melting terphenyls with their probable PCB contamination are, however, melted at autoclave temperatures and significant volatilization of these PCTs and PCBs could take place during dewaxing, or immediately upon opening of the autoclave, unless the autoclave is allowed to cool thoroughly prior to opening.

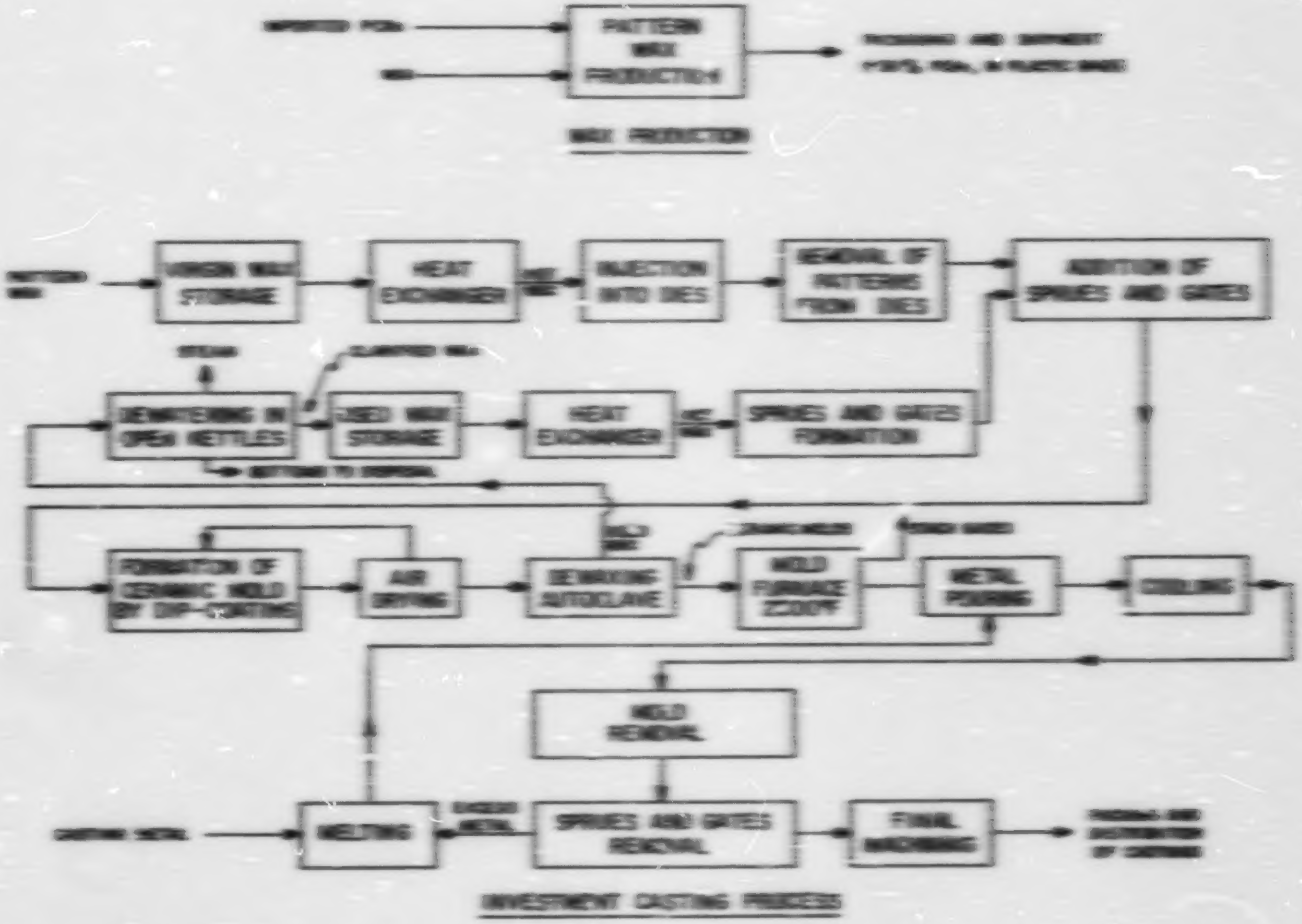

Figure 6.1 - Flow Chart of Wax Usage in Investment Casting

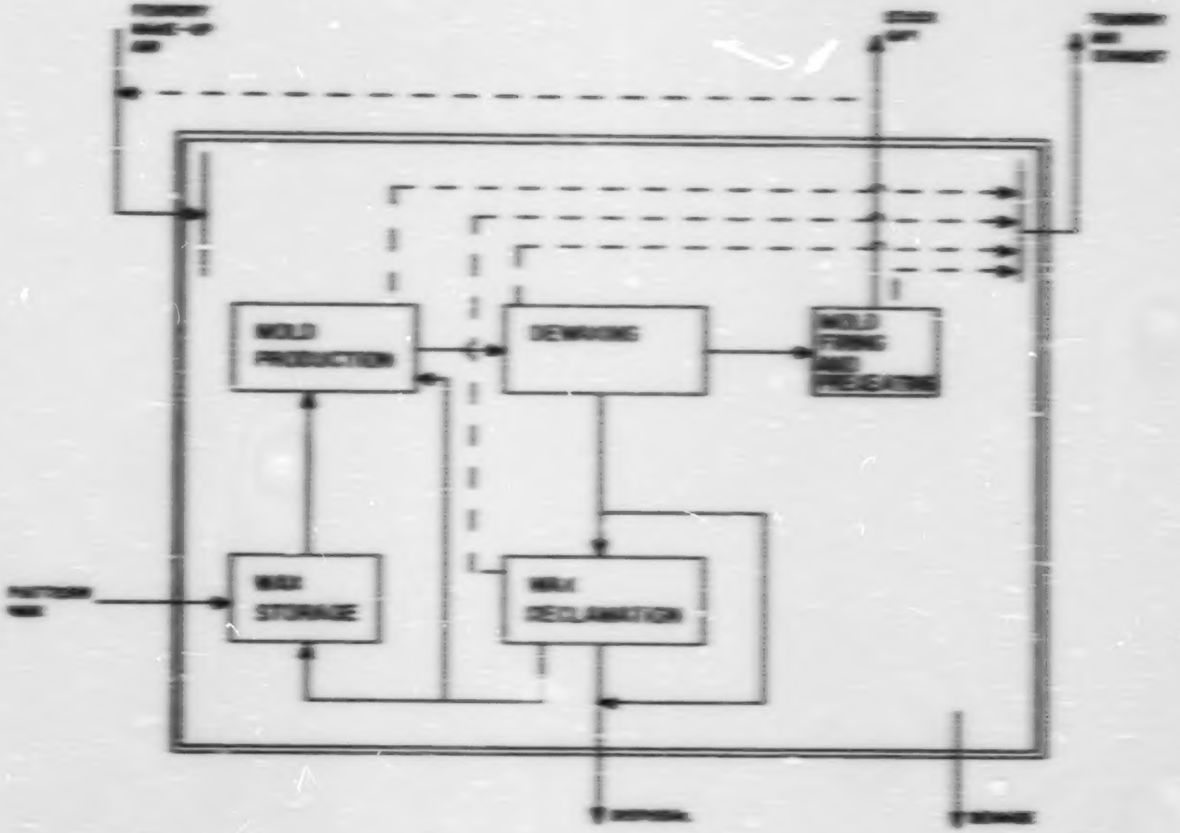

Figure 6.2 – Flow Chart Showing Probable Sources of Environmental Pollution from a Typical Investment Casting Foundry.

Volatilization during wax melting and pattern injection into the pattern dies is probably insignificant since the melting process takes place in closed kettles, and injection itself is done under pressure and at a temperature not much higher than the melting point of the wax. Further, the injected patterns are not removed from the pattern dies until they have cooled and hardened sufficiently to be removed without damage.

Losses during the wax reclamation phase of the process would mostly be carried in the water removed from the reclaimed wax. Solubility of PCBs and PCTs in water is inversely related to the degree of chlorination; thus terphenyls and any PCB contamination contained in the terphenyls would more likely produce a higher concentration in the foundry wastewater than would the decachlorobiphenyl.

The above comparisons of foundry losses of PCTs and PCB contamination with decachlorobiphenyl may make the decachlorobiphenyl appear preferable in terms of environmental pollution from investment casting foundries, but though losses may be less for the decachlorobiphenyl in the mold production, wax reclamation and dewaxing processes, the losses during the mold firing were probably greater for the decachlorobiphenyl because its greater chemical stability at high temperatures assures that if losses do take place during the mold firing operation, decachlorobiphenyl would much more likely escape destruction in the furnace and stack than the lower chlorinated PCTs with their PCB contaminant. In other words, the greater thermal and chemical stability of the decachlorobiphenyl may have minimized losses to the environment during most of the foundry processes, but losses during the mold firing operation are likely much greater for decachlorobiphenyl than for the terphenyl and its PCB contaminant.

Detailed data on the losses from the various parts of the foundry process are not available. Industry sources claim that virtually all wax components are destroyed in the mold firing operation. No known stack gas analysis has been performed to either substantiate or refute this claim; nor have analyses been performed to determine the level of PCB/PCT contamination in foundry air or wastewater.

6.3.2.3 Sources of PCB/PCT Loss to the Environment in Wax Manufacturing

Very little is known about the wax manufacturing process. However, it is known that in the process fillers are added in powdered form to the molten wax base. Processing to a desired particle size may be performed, and losses of dust to the environment by air routes from both size reduction and mixing would be expected. Chlorinated polycyclic fillers are, however, no longer used in investment casting.

With regard to the use of chlorinated polycyclic components, losses to the environment would probably result from direct volatilization of the component materials, which must be melted to be added to the molten wax. No information is available on the process temperatures, on whether the processing is done under pressure or within enclosed containers, or on the volatility of polychlorinated terphenyl compounds except for the single evaporation loss rate data point given in Section 6.6.3.2.1 - 0.03 percent in 5 hours at 163°C. No analyses of plant air or water have been performed to date.

6.4 Wax Manufacturers

Table 6.2 is a listing of investment casting wax manufacturers indicating whether they have produced or currently produce waxes containing PCBs or PCTs. Total production volumes cannot be derived from the data that have been gathered; thus production data for the several companies that have complied with requests for data are not included here since publication of such information might jeopardize their competitive positions. If sufficient information had been available to estimate the total annual volume of wax production, such a total figure would have been stated.

Table 6.2

Lists of I.C. Wax Manufacturers

Wax Manufacturer	EPA Region	Company Contact	Status of Usage of PCB and PCT in Wax Formulations: Past	Current
Alexander Saunders and Co. P.O. Box [illegible] Coldspring, New York	2	Mr. Saunders, Jr.	PCBs : Yes PCTs : No	No
M. Argueso & Co., Inc. 441 Waverly Avenue Mamaroneck, N.Y. 10543	2	Leo Argueso	PCBs : Yes PCTs : Yes	No Yes
[illegible] Corporation [illegible] Industrial Park [illegible], New Jersey [illegible]	2	Mr. [illegible]	PCBs : Yes PCTs : Yes (before Argueso's [illegible])	No No
[illegible] [illegible] [illegible], Michigan [illegible]	5	Mr. [illegible]	PCBs : No PCTs : No	No No
[illegible] Manufacturing Co. [illegible] Avenue Cleveland, Ohio 44113	5	Robert [illegible]	PCBs : No PCTs : [illegible]	No No
J. F. McCaughin Co. [illegible] Avenue Rosemead, California	9	John McCaughin	PCBs : No PCTs : Yes	No Yes
[illegible] Manufacturing Co. [illegible] Road P.O. Box [illegible] Romulus, Michigan	5	[illegible] Robert [illegible]	No compliance with information request	
Kindt-Collins 12651 Elmwood Avenue Cleveland, Ohio 44111	5	---	PCBs : No PCTs : Experimental	No Experimental
Remet Corporation P.O. Box [illegible] [illegible] Chadwicks, New York 13319	2	John [illegible]	Distributor (only) for M. Argueso & Co., Inc.	
[illegible] Co. [illegible] Street [illegible], Massachusetts	1	Mr. Griffin	PCBs : No PCTs : No	No No
Precision Cast Parts Corp. 4600 South East Harney Dr. Portland, Oregon 97206	10	Mike [illegible]	PCBs : No PCTs : Yes	No No
[illegible] Manufacturing Co. [illegible] Chicago, Illinois [illegible]	5	Paul [illegible]	PCBs : Yes PCTs : Yes	No Yes

6.5 Sources of PCB/PCT Supply

6.5.1 Domestic Sources

Polychlorinated biphenyls were produced in the United States primarily by Monsanto. Production commenced in the late 1920s and continued without interruption until April of 1971 when Monsanto voluntarily ceased production of PCBs intended for use in other than closed systems such as electrical capacitors and transformers (where they were used respectively as dielectric fluids and cooling fluids). Between 1929 and 1975 the total U.S. production of PCB formulations amounted to some 1400 million pounds, of which it is estimated 750 million pounds are still in service in some form, 55 million pounds have been destroyed, 290 million pounds are in dumps and landfills, and 150 million pounds are contained in soil, air, water, sediment, and in the bodies of animals, including humans.

By June of 1971, PCBs manufactured in the U.S. by Monsanto were no longer available for use in open systems. (There was a two-month delay between curtailment of production and depletion of stocks.) Approximately one million pounds of PCB heat transfer liquid was manufactured by Geneva Industries, Houston, Texas, from 1971 to 1973.(16) The domestic producer of PCB-filled wax did not start until after Monsanto's voluntary curtailment of production for open-ended uses. Further, it has been stated by a Monsanto spokesman that the company has never produced a PCB product that was more than 70 percent chlorinated, because high chlorination of biphenyl is difficult (the material becomes thicker and harder and more difficult to chlorinate at the higher chlorination levels), and the resultant product would be high in impurity, mainly in the form of lower chlorinated biphenyls.(12) Decachlorobiphenyl used in casting waxes has come exclusively from foreign sources; no information is available on the degree of contamination of this foreign decachlorobiphenyl.

Polychlorinated terphenyls, which have been used in investment casting waxes for more than two decades have at times been supplied to wax formulators by Monsanto and its outlets. However, in April of 1972, Monsanto ceased production of chlorinated terphenyls, and, as with PCBs, there was a several-month delay between curtailment of production and cessation of sales of PCT. At that time, Aroclor 5460 (the Monsanto PCT formulation used in casting waxes) was selling to wax manufacturers for about 20¢/lb. Once domestic production ceased, wax formulators were forced to buy from foreign sources at a cost of 20¢ to 40¢/lb. more than had been paid, with the current price of imported PCT being in the region of 70¢/lb.

Domestic production of PCTs by Monsanto through 1972 was as follows:

Year	Millions of Pounds of Aroclor 5460
1968	8.87
1969	11.60
1970	17.77
1971	30.21
1972	8.13

It is believed that a relatively small part of this production was used in casting waxes, probably on the order of half a million pounds per year. Aroclor 5460 was used primarily in adhesives, lubricants, and paper coatings.

6.5.2 Imports

Imports of decachlorobiphenyl and polychlorinated terphenyl used in investment casting waxes are thoroughly discussed in Section 2.0.

6.6 Alternative Pattern Materials and Wax Fillers and Components

There are many materials and classes of materials that can be used for patterns for investment casting. The main material classes are: waxes (natural and synthetic), resins (natural and synthetic), and low-melting metals (specifically, mercury and tin). The waxes and types of resins commonly used as pattern materials can be classified under the general heading of *thermoplastics*, though it is likely that the use of *thermosetting* resins has been investigated and these materials could conceivably be used as pattern materials (specifically, as fillers) for some casting applications. Generally the thermoplastics provide the greatest ease in handling and pattern production since thermosetting resins require heat and pressure or the addition of catalysts to affect curing, which is an exothermic process for most if not all thermosetting resins; high temperature differentials and long cooling periods influence the pattern's dimensional tolerances and increase the pattern production cycle time.

6.6.1 Previously-Used Pattern Materials

In a special exhibit in the gem room of the Smithsonian Institution several years ago were gem-studded gold investment castings of flowers and small shrubs. In addition to the monetary value, the exhibit was technically interesting in that the patterns for the gold castings consisted of the actual flowers and shrubs. The jeweler who made the castings had apparently invested the flora in appropriate investment material and then, when the investment had hardened, he burned the organic matter out of the mold and poured the gold in.

Generally twigs and flower petals do not make good pattern materials because they "ash" when burned - that is, they leave behind the non-volatile residues of the original organic structure. But for this one special application, in which production rate was not a consideration, the jeweller/artist could take the time to use compressed air or some other gas to blow the ash material from the crevices of the investment mold. Such diligence in the investment casting industry, however, would defeat the cost effectiveness of the process; pattern materials must burn clean and leave no residue, or minimal residue, in the investment mold.

Many thermoplastic pattern materials have been used and have been suggested for use over the years. As the name "lost wax" indicates, true waxes, such as natural waxes, beeswax and the like, were originally used as thermoplastic pattern materials. As other pattern materials were sought to improve the properties of disposable patterns, other natural thermoplastic materials, such as gum damar, gum esparto and other resins, plus mineral waxes of the type extracted from soft coal, and petroleum waxes were adopted for use. Modified waxes, such as micro-crystalline waxes were developed for use and are currently used in investment cast procedures.(2) (Appendix B is a glossary of wax related terms.)

As has been mentioned in other parts of this report, mercury and tin can be, and have been, used to make patterns. In the mercury process, mercury is frozen into the desired shape in the pattern die; it is then removed from the die and invested with appropriate material, and then the mercury is melted out. Any mercury remaining in the mold is vaporized during the mold-preheating process. The difficulties with mercury are toxicity, the need for very low process working temperatures (-35° to -70°F), and the hazards of the mercury cleaning process which entails acid handling. Also, mercury is expensive. These disadvantages more than offset the advantage of the mercury pattern process - namely, that the castings produced have extremely good surface finish, better than can be obtained with the best casting waxes currently used, and, since mercury does not significantly change volume in going from a solid to a molten state, no great stresses are put on the mold during meltout, as with thermoplastic patterns. This latter advantage assures very high tolerances of the cast product. According to the Investment Casting Institute, mercury is no longer used as a pattern material in the United States.

Tin patterns also result in high quality castings. Tin melts at a higher temperature than do the currently-used thermoplastic materials, which means that the pattern die material must have higher temperature capabilities than are necessary for the manufacture of wax patterns, and the tin-handling and injection equipment must withstand the higher temperatures. The result is higher capital cost for equipment and/or reduced pattern-die life.

Modern investment casting procedures rely almost exclusively on thermoplastic pattern formulations which, depending upon the type of metal to be cast and the shape of the casting, may be filled or unfilled.

6.6.2 The Ideal Pattern Wax

The ideal pattern material would have these properties:

- No change in volume during heating, cooling, melting or solidifying
- High conductive heat transfer coefficient, for rapid cooling after injection into the pattern mold
- Narrow temperature range over which melting and solidifying take place
- Hardness at all temperatures up to the melting point
- Zero ash content; should burnout cleanly from the investment mold
- No toxic components, and no toxic byproducts produced during burnout
- No oxidation or gum formation potential in the injection equipment
- Good surface finish, accurately following the internal surface finish of the pattern die
- Ceramic slurry should adhere well to it but not attack or dissolve its surface
- Weldability, so that multiple patterns can be affixed to a central pouring basin and sprue

6.6.3 Filled and Unfilled Waxes

The single greatest difficulty with investment casting waxes is the change in volume that accompanies melting, solidification and, in general, temperature change. (This problem has been discussed in Section 5.0.) To reduce this temperature-induced volume change, filler materials of various kinds can be added to the wax formulation. Typical filler materials are powders having the following properties:

- They melt or sublimate at a much higher temperature than the basic wax formulation, which means they remain in the solid phase throughout the entire investment casting process, except during mold burnout and preheat
- They must have good heat transfer properties
- They must have a specific gravity that is close to that of the wax, in order to minimize the need for continuous agitation to keep the filler material in suspension in the wax prior to injection into the pattern die
- They must leave minimal ash or other residue in the investment mold when the pattern wax remaining in the mold after the de-waxing operation is burned out of the mold
- They should exhibit a very low volume change as a function of temperature
- They should be safe to handle and should present minimum toxic hazard to foundry workers, and to the environment in general

The chief functions of fillers in waxes are to increase the cooling rate and to control volume shrinkage during cooling and solidification of the pattern. To the extent they serve these purposes, filled waxes simplify the pattern making process and thereby reduce the process costs. Filled waxes, however, cannot be used in all investment casting operations. Foundries having older equipment may not have the facilities for continuous agitation of the melted wax prior to injection into the pattern die. If the wax is not agitated the filler material will rise or sink (depending on its specific relative to the liquid wax) and will not be uniformly distributed in the pattern after the wax is injected into the pattern die. The result could include clogged injectors and poor-quality patterns, the latter being caused by differential cooling and shrinkage within the pattern.(5)

One other instance where filled waxes are not used is in applications where the filler particles might be too large to allow the pattern wax to flow into the finer crevices of the pattern die; a good example is the casting of turbine engine blades where the edges of the blades have very small radii of curvature and the use of filled waxes would cause a low-quality edge to be produced on the pattern.(17)

Filler materials that have been and are being used include:

- wood flour
- polystyrene beads or powder
- carbon microspheres
- urea powder
- polyols (e.g., pentaerythritol)
- various organic acids (e.g., cyanuric, fumaric, isophthalic, adipic)
- decachlorobiphenyl

Unfilled waxes contain no solid components when the wax is molten. All of the components melt together and are mutually miscible, and continuous stirring of the wax is not necessary to maintain the components in proper distribution. Unfilled waxes do contain resinous materials, and polychlorinated terphenyl has been a commonly used resin component.

Typical wax components of an unfilled wax are:*†

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†The terms used in this list are defined in Appendix B.

- Hard Waxes
    - Vegetable wax (candelilla)
    - Vegetable wax (carnauba)
    - Mineral wax (montan)
    - Synthetic wax, nonchlorinated
    - Synthetic wax, chlorinated
- Microcrystalline Waxes
    - Petroleum origin, high m.p. (175°F)
    - Petroleum origin, low m.p. (145°F)
    - Insect origin (beeswax, USP)
- Soft Resinous Plasticizers
    - Rosin derivatives
    - Terpene resins
    - Coal-Tar resins
    - Petroleum hydrocarbon resins
    - Chlorinated resins
    - Elastomer polymers
- Hard Resins
    - Rosin derivatives
    - Terpene resins (from plants)
    - Coal-tar resins
    - Petroleum hydrocarbon resins
    - Chlorinated resins
- Modifiers
    - Synthetic wax, nonchlorinated
    - Elastomer polymers
    - Polyethylene resins

A typical wax formulation would be:*

Hard wax	40%
Microcrystalline wax	25%
Soft resinous plasticisers	15%
Hard resins	20%
Antioxidant	0.05%

Polychlorinated terphenyl is classified under the headings of Hard and Soft Resins, Chlorinated. PCT has been in use in waxes for more than 20 years and is still being used. That hard and soft resins constitute only 35 percent in the example cited above is on the low side, at least with respect to the use of PCTs which usually constitute about 40 percent of the wax composition.

6.6.3.1 PCBs

The only polychlorinated biphenyl used in investment casting waxes was decachlorobiphenyl, and it was used as a filler in pattern waxes by only one manufacturer. Use of decachlorobiphenyl in waxes ceased in the middle of 1976.

6.6.3.2 PCTs

6.6.3.2.1 Function of PCTs in Waxes

The polychlorinated biphenyl currently used in waxes is a product imported from France called Electrophenyl T-60. The number 60 apparently makes reference to the chlorine content, 60 percent of the weight of the material, which indicates a rather high degree of chlorination - sufficient to make the material solid at room temperature.

Prior to April of 1972, PCT formulations could be purchased from Monsanto. As of that time, however, Monsanto ceased production of polychlorinated terphenyls for all open-system applications, including investment casting since the bulk of the PCT eventually is either volatilized into the atmosphere or disposed of along with otherwise unreclaimable wax. The Monsanto product used prior to 1972 was designated as Aroclor 5460; the 54 designates terphenyl, the 60 designates the weight percent of chlorine content. The following are the properties of Aroclor 5460:(18)

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Appearance: clear, yellow to amber, brittle resin or flakes
Chlorine content: 58.5 to 60.6 percent
Acidity: 0.05 mg KOH/g (maximum)
Average Coefficient of Expansion: 0.00179 cc/cc/°C (25° to 124°C)
Specific gravity: 1.670
Density: 13.91 lb/gal at 25°C
Evaporation loss: 0.03% in 5 hours at 163°C
Flash point: none to boiling point
Fire point: none to boiling point
Softening point: 208° to 222°F
Refractive index: 1.660 to 1.665

As a resin component in investment casting waxes, PCTs serve the function of increasing the hardness of the wax patterns and making the patterns cool faster and with less shrinkage in the pattern die.

5.6.3.2.2 Dependence of the Investment Casting Industry upon PCTs

At the beginning of this study, the main issue was the extent to which the investment casting industry was dependent upon PCBs. The use of PCBs in waxes was discontinued in the middle of 1976, after a period of about three years of use, and the impact on the industry as a whole has been small. The single producer of PCB waxes was influenced by state legislation controlling PCB use and by impending Federal legislation as well as by the adverse publicity associated with PCBs. No data are available on the economic impact on this one wax producer as a result of cessation of PCB wax production.

PCTs are more widely used in the industry and have been used for several decades. Thus the industry is more dependent upon the use of PCTs than it was upon PCBs. Of the 11 wax formulators listed in Table 6.3 (12 are listed, but one is merely a distributor for one of the others), three currently have product lines containing PCTs, whereas six manufacturers have at some time produced PCT waxes. Of the three currently producing PCT waxes, at least two are down-playing their PCT wax lines, because they expect that pending environmental legislation might ban the use of PCTs.

One wax formulator, Freeman Manufacturing Company in Cleveland, Ohio, terminated production of PCT waxes around the beginning of 1975, a move that was apparently to some degree environmentally altruistic since there were not any really adequate substitutes for the PCT waxes at that time and the company did loose a portion of its business until adequate substitutes were found. Freeman also terminated its production of wax lines containing nitrogen compounds because the nitrogen-containing waxes may generate toxic compounds during the burnout and preheat phase of the investment casting process. (The disadvantages of nitrogen-containing alternatives to PCTs are discussed in Section 6.6.5, Environmental and Toxicological Considerations of Alternatives.) The experience of the Freeman Manufacturing Company shows that, at least as far as the wax formulators are concerned, PCTs are not an essential ingredient; and they have been able to cease production even though PCT waxes continued to be available from competitors. Thus it does not seem unreasonable to surmise that an industry-wide restriction on the use of PCTs would not have a significant effect on the wax producers, except insofar as such a restriction might impact on the wax formulators through some kind of feedback mechanism from the investment casting foundries, which, of course, is where the final test of waxes is made.

In the 150 or so investment casting foundries in this country the various wax formulations perform their functions of providing patterns from which molds can be made for the precision casting of medium to high temperature metals and alloys. Where the cast products are designed with generally small cross-sectional areas, cooling shrinkage of waxes can have a negligible effect on the final cast product, and lower-cost waxes will serve the purpose adequately; but where section thicknesses are large enough that wax shrinkage could cause surface "dishing" or "cavitation", filled waxes or waxes that otherwise compensate for cooling shrinkage are essential to producing high-quality castings. Thus the question becomes one of whether or not there exist unfilled non-PCT waxes that perform adequately. Such waxes do exist and are being used. At least one foundry, the General Electric Foundry in Albuquerque, New Mexico, has been able to produce its cast products with waxes that contain neither PCBs or PCTs.(19) (General Electric is presently preparing a report on the economic and technical details of their recent changeover to nonchlorinated waxes.)

6.6.4 Alternatives to PCTs in Investment Casting Waxes

Currently only three casting wax manufacturers produce waxes containing PCTs as a resin component. One manufacturer is currently experimenting with PCTs in waxes, and the other seven wax producers shown in Table 6.2 produce waxes that do not contain PCTs. Of these seven who do not produce PCT waxes, one, Freeman Manufacturing Company, stopped production of PCT waxes in the early part of 1975 because of the environmental controversy surrounding chlorinated hydrocarbons. Freeman also terminated production of waxes containing nitrogenous components which, during high temperature decomposition, generate cyanide or nitrogen oxides depending upon whether the thermal environment is reducing or oxidizing. Freeman claims to have found PCT alternatives that perform adequately in casting waxes, but details as to the actual materials are proprietary and not available. Freeman is among the largest of the investment casting wax producers, and that this company was able to voluntarily cease production of PCT waxes tends to belie the claims of other producers that there are no adequate substitutes for PCTs.

It is evident from the material covered thus far that an alternative material to PCTs must have nearly the same properties of PCTs in casting waxes; that is, the alternative material must produce a wax product that has a narrow melting-temperature range, good heat transfer so that the patterns solidify rapidly in the pattern die, and the wax must be hard up to temperatures close to the melting point.

To achieve these wax properties, the alternative material must be a thermoplastic material that is miscible with and melts at about the same temperature as the other wax components. The properties of the domestically-produced terphenyl (Aroclor 5460) are listed in Section 6.6.3.2.1. Since the imported terphenyl is chlorinated to the same extent (i.e., 60 percent by weight) it is likely the imported material has similar properties, unless it contains additional components the Monsanto product was free of, or vice versa.

The relatively higher melting point of the terphenyl relative to the other wax components, which typically melt at 40 to 50 degrees Fahrenheit lower temperature, is not a concern once the components are mixed so long as the product wax has suitable bulk melting properties. Similarly, terphenyl alternatives need merely fulfill the bulk property requirements of the final wax product.

Since polychlorinated terphenyl constitutes a resin component in the waxes, a suitable alternative would most likely be a resin too - or, in the more general sense, a thermoplastic, even though in common usage this term is usually applied to synthetic high polymers and does not include natural resins.

Resins can be classified as natural or synthetic, and the synthetics can be either thermoplastic or thermosetting, as shown in the following outline with examples (Appendix B is a glossary containing additional information on these materials):

I. Natural Resins - rosin, balsam, kauri, congo, damar, mastic, copal, sandarac, shellac

II. Synthetic Resins

A. Thermoplastic Resins - acetal (copolymer, homopolymer), acrylic, cellulosic resins (acetate, nitrate, butyrate, propionate, ethylcellulose), polycarbonate, polyolefin (polyethylene, polypropylene, polybutylene), polystyrene, polyvinyl halide

B. Thermosetting Resins - amino-aldehyde (melamine), polyester (allyl, alkyd), epoxy, ionomer, phenolic

Many of the resins listed above have been used in investment casting waxes, especially the natural resins. The synthetic thermoplastic resins are the most likely source of alternatives to PCTs since the synthetics can be, to an extent, tailored to specific applications. Polyethylene, for instance, has been and is being used to some extent in waxes, and the properties it confers on the wax are a function of the molecular weight of the polyethylene. Polyethylene has a high coefficient of thermal expansion, however, which makes it an unlikely substitute for PCTs. (Polyethylene serves to increase the strength of the hardened wax.)

Ethylcellulose is another synthetic thermoplastic resin that has been extensively tested in casting waxes, but it has a tendency to increase the viscosity of the wax to unacceptable levels.

Polystyrene is a thermoplastic that is widely used by itself as a pattern material. Polystyrene beads have been used as filler material in waxes because its high melting temperature allows it to stay solid when the wax formulation is melted. Other high-melting thermoplastics can also serve the function of wax filler, which does not qualify them as potential PCT substitutes.

To the extent that molecular weight can be controlled, synthetic resins of both the thermoplastic and thermosetting kinds can be used as fillers or components in waxes. Polyethylene has already been mentioned. Acrylic resins can also be tailored in this manner.

Thermosetting resins tend to harden irreversibly at high temperatures because of molecular cross-linking processes; however, it is possible that high molecular weight polyester resins which might be solids at room temperature but which might be meltable a sufficient number of times to make them miscible with the other wax components and to be injected into a pattern die might have some applicability in waxes, but they might also cause problems in injection equipment as a result of hardening or gum formation in the high-pressure molten-wax lines. Generally, thermosetting resins probably have more applicability as fillers than as resinous components.

Alternatives to PCTs have been found and are being used by at least one wax manufacturer. Specific information on the alternative materials is proprietary and unavailable at this time. Since this information is not patented, it might be that the material or materials that can replace PCTs are already widely known in the wax manufacturing field as prior use precludes patenting.

Potential alternatives to PCT will not likely come from the class of thermosetting resins, except for the high molecular weight ester resins which are solid at room temperature but which melt at elevated temperature.

There are many potential wax components. According to one source, "all hydrocarbon resins and all ester resins, which number in the hundreds", have some applicability in casting waxes.(17) The problem is to find the one material, or combination of materials that adequately serve the purpose of PCTs for the three manufacturers still producing PCT waxes.

6.6.5 Environmental and Toxicological Hazards of Alternatives

The general lack of concrete information on PCT alternatives has not made it possible to comment on the potential hazards of alternatives to PCT waxes.

In choosing to discontinue its production of PCP waxes, Freeman Manufacturing Company also decided not to produce any wax formulations containing nitrogen in any significant amount, and the reasons are worthy of consideration with respect to PCP alternatives. Nitrogenous components decompose during the burnout phase of the ceramic mold preparation when the wax remaining in the mold after dewaxing is volatilized and burned from the mold. If the chemical environment of the furnace used for burnout and mold preheating is oxidizing, the nitrogen compounds have a tendency to form nitrogen oxides, some of which are acutely toxic and some of which contribute to photochemical smog problems in urban areas. If the furnace atmospheres are reducing - which is actually rare in investment casting furnaces since the objective during mold burnout is to oxidize the organic material from the mold - nitrogenous compounds tend to form cyanide compounds, the hazards of which are well known.

Bibliography - Section 6.0

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7.0 PCBs AS IMPORT COMPONENTS

Polychlorinated biphenyls may be components of imported machinery and electrical equipment and thereby may not be registered with U.S. Customs as PCBs. A specific recent instance involved the importation of transformers from Germany through Canada to the U.S. and entailed some 500,000 lbs of askarel.

In 1975, Wheelabrator-Frye, Inc., of Pittsburgh, Pa., took delivery of 256 transformers from Trafo Union (a division of Siemens, A German company) located in Montreal. In 1976, Wheelabrator-Frye took delivery on 256 additional transformers. All of these 512 transformers were askarel filled prior to importation; they were all the same model, and they were subsequently sold by Wheelabrator-Frye to a utility company for installation and use in electrostatic precipitators. Each transformer contained about 94 gallons of askarel. In the early part of 1977, 256 more transformers of the same model were imported to Wheelabrator-Frye for purchase and installation by the same utility customer, but these last transformers, at the specification of the utility company, were mineral oil cooled rather than askarel cooled. Wheelabrator-Frye says that the importation of precipitator transformers for this customer is completed. It is expected that none of the transformers will be in service until the end of 1977. Wheelabrator-Frye will supervise the installation of the precipitators and the utility will maintain ownership of the transformers after installation. According to Wheelabrator-Frye, the importer is listed with U.S. Customs as Siemens. (1)

Sources of Information - Section 7.0

1. Personal Communication with one Mr. Hatch of Wheelabrator-Frye, Inc., of Pittsburgh, Pa.

8.0 CONCLUSIONS AND RECOMMENDATIONS

There are only four manufacturers that are currently directly reliant upon imported polychlorinated polycyclic compounds. They are:

Joy Manufacturing Company, Pittsburgh, Pennsylvania - Sole user of heat transfer fluids for the cooling of mining machinery; the specific PCB formulation is called Pyralene and it is imported from France.

J. F. McCaughlin Company, Rosemead, California - Uses imported polychlorinated terphenyls in investment casting waxes.

Yates Manufacturing Company, Chicago, Illinois - Uses imported PCTs in investment casting waxes.

M. Argueso & Company, Mamaroneck, New York - Uses imported PCTs in investment casting waxes and tooling compounds.

Recommended steps to control the uses of imported PCBs need no longer be considered since the Toxic Substances Control Act specifically addresses the PCB problem (Section 6(e), Public Law 94-469), and states that imports must cease as of one year after the effective date of the Act, except for those uses where the PCBs will be totally enclosed (specifically in electrical transformers and capacitors) or where an exemption has been granted. Paragraph (2) subparagraph (A) states that "effective one year after the effective date of this Act no person may manufacture, process or distribute in commerce or use any polychlorinated biphenyl in any manner other than in a totally enclosed manner." The Act became effective on January 1, 1977. Importation is defined in the Act as manufacture.

The single use of imported PCBs is in the maintenance of a line of PCB-containing mining machinery that Joy Manufacturing Company produced up until several years ago. (Production of PCB-containing Joy continuous miners terminated in 1970; PCB-containing Joy loaders have not been produced since 1973). Since mining machinery does not qualify as use of PCBs in "a totally enclosed manner", the currently operable machinery will have to be either modified so that it is not dependent upon PCB cooling fluids or it will have to be put out of service at the end of 1977, unless the EPA formally finds that continued use of PCBs will not present an unreasonable risk of injury to health or the environment in accordance with the provisions of Section 6 (e)(2)(B) of the Act.

As shown in Section 3.0 of this report, the PCB-containing Joy machinery accounts for the following percentages of all equivalent mining machinery currently operable:

loaders = 15.6% (350 Joy loaders)
continuous miners = 2.5% (50 Joy miners)

PCB fluids are used in the motors of the mining machinery (two motors in each loader and three motors in each continuous miner) as heat transfer fluids. For the loaders, dry-motor conversion kits are available from Joy at a total conversion cost of about $6,200 per loader. (1) Thus the total conversion cost for the approximately 350 currently operable loaders is on the order of $2.2 million and will have to be borne by the owners of the machinery.

No equivalent dry-motor conversion kits are available for the continuous miners since the motors are larger and dissipate more heat than dry motors of the same physical size could handle. However, if the entire cutting-head assemblies on each miner are replaced - cost about $65,000 per miner - the total cost to the owners of the 50 or so operable miners would be about $3,250,000. Otherwise, the replacement cost for the 50 miners at about $300,000 each would be $15 million. (1)

The following considerations should be kept in mind with regard to the continuous miners:

(a) The last of the PCB-containing continuous miners was built by Joy in August 1970; thus most of these machines are more than 7 years old.

(b) The typical service life of these miners is at least 10 years. (2)

(c) Although the number of miners considered currently operable is about 50, the number in actual operation is possibly considerably less than this. (2)

(d) The Organization for Economic Co-Operation and Development, of which the U.S. is a member, issued a decision on February 13, 1973, (see Appendix C-1) stipulating that member nations restrict the use of PCBs in all but four categories of use, one of which includes mining machinery. This OECD precedent might be useful to the owners of PCB-containing Joy mining machinery in petitioning for a temporary exemption from Toxic Substances Control Act.

With respect to imported polychlorinated terphenyls used in tooling compounds and investment casting waxes, the following points should be noted:

(a) Terphenyl-containing investment casting waxes currently cost 15¢ to 25¢ per pound more than non-terphenyl waxes; manufacturers who produce terphenyl waxes claim that their terphenyl wax sales are less than half of their total wax sales.

(b) Of the eleven investment casting wax manufacturers, at least six produced terphenyl waxes at the beginning of this decade; now only three do. Of the three that ceased production of terphenyl waxes, one stopped when domestic terphenyls became no longer available, and one of the remaining two, if not both, voluntarily chose to stop using chlorinated and nitrogenous components in its waxes. The companies that have terminated production of terphenyl waxes are still in business, and there is no evidence that their competitive positions have been unfavorably affected.

(c) Since some wax manufacturers have terminated production without substantial adverse economic impact on sales and operations, it is reasonable to conclude that PCTs are not essential to the adequate performance of investment casting waxes. One of the current manufacturers of terphenyl waxes says there are no suitable substitutes for PCTs, even though other manufacturers seem to have found some. If terphenyl waxes perform in such a way as to, say, reduce the number of rejected castings from 3 percent to 2 percent, then this one producer who says there are no suitable alternatives to terphenyls may be speaking in the context of the 50-percent reduction of rejected castings terphenyls might afford. However, this same hypothetical statistic can be also interpreted as meaning that terphenyl waxes increase the number of successful castings by only slightly more than 1 percent.

(d) Of the approximately 150 investment casting foundries, at least one large foundry voluntarily terminated its use of waxes containing PCBs or PCTs. This foundry is owned by the General Electric Company and produces the highly precise components for the General Electric line of turbine engines that are widely used in commercial and military applications, both domestically and internationally. If there are applications that are more critically dependent upon the accuracy and precision of the investment casting process, they have not been uncovered in this study.

These above considerations should be kept in mind in considering methods for controlling the uses of imported PCTs. The following control options are suggested:

1. Since PCTs may contain PCBs in concentrations exceeding 0.5 percent, PCTs might be treated as PCB mixtures and accordingly importation could be banned under Section 6 (e) of the Toxic Substances Control Act. However, imported PCTs currently being distributed in the U.S. are certified by the distributor as containing less than 0.05% PCBs.

2. If the concentration of PCBs in PCTs should be found to occasionally exceed 0.05%, the EPA can take action under Section 6 (b) of the Act to assure adequate quality control. Actions authorized under this section include requiring the manufacturer or processor to repurchase contaminated material.

3. If, in accordance with Section 6 of the Toxic Substances Control Act, PCTs are shown to "present an unreasonable risk of injury to health or the environment", then imports of PCTs would be banned under Section 13 of the Toxic Substances Control Act.

Sources of Information - Section 7.0

1. Telephone communications with C. W. Fitzgerald, Product Manager for Loaders and Continuous Miners, Joy Manufacturing Company, Pittsburgh, Pa.

2. Telephone communication with Prescott Green, Joy Manufacturing Company, Pittsburgh, Pa.

APPENDIX A

METAL FORMING TECHNIQUES: COMPARED WITH INVESTMENT CASTING

Manufacturing processes by which parts or components are fabricated from metal stock entail metal forming. The five major metal forming methods are listed in the outline below, which includes a further breakdown on the specific processes:(1)

I. Metal Working
  A. Forging
  B. Extrusion
  C. Rolling
  D. Drawing
  E. Sheet-forming processes

II. Powder and Fiber Forming Processes

III. Electroforming

IV. Joining Processes
  A. Welding and brazing
  B. Mechanical joining - riveting, screwing, bolting, bonding

V. Casting(2)
  A. Sand casting (a.k.a. Aggregate Molding)
    1. Shell molding
    2. Carbon dioxide process
    3. Investment casting
    4. Ceramic molding
    5. Plaster molding
  B. Permanent mold casting
  C. Die casting
  D. Centrifugal casting (also considered to be a permanent mold process)

A given metal forming process is a factor in the satisfactory service performance of a manufactured part in that it affects the microstructure, physical properties, and surface finish of the metal. The chosen process may also introduce large residual stresses into the part and it may influence final design which, in turn, influences service behavior. The more important factors to be considered in choosing an optimum metal forming process (or combination of processes) include: type of material, metallurgical structure effect inherent in the process, size of the part, shape or complexity of the part, tolerances or finish required, quantity to be produced, cost, and production factors such as availability of equipment, rate of production, and time required to initiate production.

The particular metal or alloy specified for a part is important in the selection of the forming process. Some aluminum or copper alloys may be fabricated by practically any of the manufacturing processes; other alloys may be brittle under cold-working conditions but may be hot-worked. Highly refractory materials, such as tungsten and tungsten carbide, are not suitable for casting and must be fabricated by powder-metallurgy (P/M) methods. P/M is also used for making porous metal products, or parts requiring combinations of two or more materials (e.g., metals combined with ceramics). P/M combinations of different metals are not alloys in the traditional sense. Alloys that are extremely hard, and therefore unsuitable for machining operations, can be precision cast (i.e., investment cast) and then ground if extremely close tolerances are required. Higher-melting-point alloys such as steel can be fabricated by most of the major classes of processes but are not suitable for all of the individual processes within a major class. Where a specific material must be used, the choice of the optimum fabricating process becomes more limited. The formability of a material may be predicted either from the reduction of area or the percent elongation in a tension test; the higher these values, the better is the formability. Other factors that influence formability are rate of deformation, temperature, type of loading, environment, impurities in the metal, and surface condition of the original stock.

Each manufacturing process has a different effect on the microstructure of the metal and, consequently, on its bulk mechanical properties. Casting processes generally produce relatively coarse-grained microstructures and random orientation of nonmetallic inclusions. The result is isotropic properties, but lower ductility than wrought products. Castings may also be porous, particularly sand castings. Hot-working processes, such as forging, align the inclusions (fiber structure) and thus impart anisotropic properties, with the strength and ductility generally being higher in a direction parallel to that of the inclusions; such orientation may be an advantage or disadvantage, depending upon the direction of the applied loads. Cold-working processes (such as cold rolling) also produce directional properties in the metal because of the tendency of the grains (or crystals) to align in the direction of maximum deformations. In addition the grains become distorted, and the metal becomes harder and stronger but less ductile. Cold-working operations (or any process causing nonuniform deformations) generally leave residual stresses in the part. Residual stresses left in a part arithmetically add to the stresses induced by service loading, and in some instances residual stresses are of major importance, either advantageous or disadvantageous depending on the given application.

Metal-forming processes may be limited as to the size of the part they can produce. Among the processes that are limited to relatively small parts are precision investment casting, die casting, and powder metallurgy. Large parts are best produced by sand casting, forging, or fabrication of component sections by welding or other joining processes. Parts with axial symmetry can be produced by turning and spinning operations; other large parts, such as domes, made of sheet or plate stock can be formed by explosive-forming techniques.

The geometry of a part often dictates the process or combinations of processes used in its manufacture. Generally, castings can be more complex than parts made by most other fabrication processes; however, some casting processes - sand and precision investment casting - are capable of producing parts of greater complexity. Parts produced by powder metallurgy have definite restrictions as to design because of the inability of metal powder to flow like a liquid. In some instances the complexity of a part may require the fabrication by the welding or brazing of component sections. The change from forming a part as a single piece to fabricating it from several sections usually requires design modifications if optimum serviceability and cost effectiveness are to be maintained.

Parts requiring close tolerances or smooth finishes can be formed directly by precision investment casting, die casting, permanent-mold casting, or such cold-working processes as swaging, drawing, or stamping. If formed by other processes, they can be finished by machining or grinding. Hot-working processes, such as forging, result in relatively rough, oxidized surfaces and low dimensional accuracies. Welding operations generally result in distortion or dimensional change. Cost often governs whether the desired tolerances should be attained in the original forming process or in secondary operations. For instance, in hot-working operations, such as rolling, forging, and extrusion, surface roughness ranges from about 100 to as high as 2000 microinches, while in machining operations, such as grinding and honing, surface finish can be as fine as 1 microinch.

The number of parts to be produced is important in choosing the method of manufacture. Some processes are suitable only for large-quantity production because of high tooling costs; examples are permanent-mold and die casting, certain forging processes, deep drawing, and precision investment casting. Processes such as sand casting, spinning, and welding are readily adaptable, but not necessarily restricted to, small-quantity production.

If the quantity to be produced is large, the overall finished cost of the product is usually the prime consideration in the selection of a process. In most cases cost is the deciding factor in choosing both the material and the fabrication process.

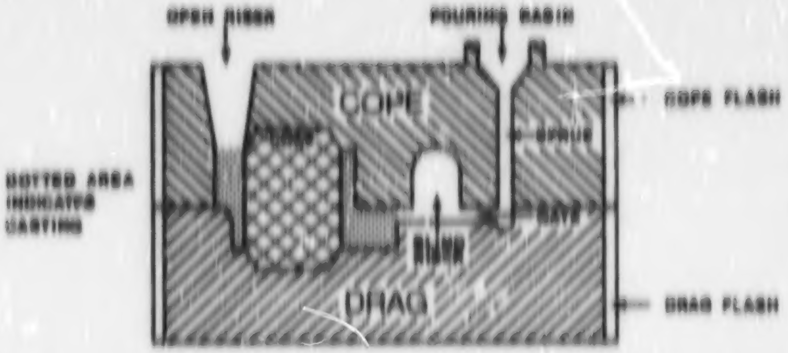
In some instances the time necessary to tool up for production may be of significance in selecting the fabrication process. Forming methods entailing extensive tooling require long lead times before production can commence. Another important production factor is the required rate of production. Processes such as die casting, powder metallurgy, and deep drawing have high production rates. Conversely, sand casting, spinning, hydraulic press forging and welding are relatively slow processes.

Strength levels for metals range from as low as 1000 psi to the order of 500,000 psi. Size of parts may range from a thousandth of an inch to a few feet. Rates of deformation can be as high as 40,000 fpm, as in explosive forming, while working temperatures can be as low as cryogenic to the range of 4000°F. Capacities of equipment for forming metal components are as high as 50,000 tons, with a 200,000-ton hydraulic forging press presently in the design stage.

Casting Techniques

Sand Casting(2)

Sand casting has been and is currently the method by which the largest number of castings are produced. Typical products include cast iron automobile engine blocks and crankshafts, furnace and boiler parts, manhole covers, aluminum pistons and bronze jewelry. The most common molding material is known as green molding sand, which is a mixture of sand, clay, water, and other materials that add to the hot strength and thermal stability of the mold and to the surface finish of the cast product. The *pattern* - that is, the object used to make the impression to be cast in the sand is usually made of wood, plaster or metal and is used to make the two halves of the mold, the *cope* (the upper portion of the mold) and the *drag* (the lower half). After the pattern impressions have been made in the cope and drag, the two halves are weighted down or fastened together to keep the cope from floating when the molten metal is poured.



Section through a sand mold showing the various parts.

In the diagram the features shown are the cope, drag, risers (blind and open), gates, sprue and core. The meanings of these terms are applicable to all forms of casting. A riser is a reservoir of molten metal which feeds metal to the casting to compensate for shrinkage as the poured metal solidifies. The sprue is a vertical connection between the pouring basin and the gating system which distributes the metal in an optimum fashion to the volume of the mold where the cast product will form. The design of the gating system also controls the rate of entry of the metal into the mold cavity; it minimizes turbulence, allows air and other gases to escape, and establishes the proper temperature gradient to minimize shrinkage cavities.

Sand casting can be used for almost all castable materials. Labor and equipment costs are low so that sand casting is economical for small-quantity jobs. Minimum section thickness for objects cast in the traditional sand-casting methods are on the order of 1/8th inch. (Though investment casting can be classed as a type of sand casting, section thicknesses of investment castings are frequently less than 1/8th of an inch.) Surface roughness ranges between 250 and 1000 microinches, rms.

Other casting methods that use aggregate molding materials, but which otherwise are not referred to as sand casting, are shell molding, carbon dioxide process, ceramic molding, plaster molding, and of course investment casting.

Shell Molds(3)

Shell molding was developed in Germany during World War II and was unknown outside of Germany until after the war. It is sometimes referred to as the "Croning", or "C", process, after its inventor. The process consists of making molds and cores as relatively thin shells, about 1/4 inch thick. Fine sand (usually silica), of 100 to 150 mesh, is used, and imparts smooth surfaces to the castings. The sand is thoroughly mixed with about 3 percent of a suitable synthetic resin; a two-step phenol formaldehyde resin is commonly used. Metal pattern plates, similar to cope and drag pattern plates, are heated to a temperature between 400 and 500°F; to prevent the shell from sticking to the pattern plate and thereby preventing its proper removal, a silicone release agent is sprayed over the hot pattern surface. The hot pattern is then fastened to a "dump box" containing the sand/resin mixture; the pattern surface faces the opening of the dump box. When the dump box is quickly inverted, the sand/resin mixture falls on the hot pattern surface. The heat penetrates the mixture and softens the resin, making the binder effective. After about 8 to 20 seconds, depending upon the shell thickness desired and other variables, the dump box is rotated back to its normal position. The powder mixture that has not been affected by the heat falls away, leaving a shell adhering to the pattern. Heat first causes the resin to become sticky; additional heat cures or hardens it. For the additional curing, the pattern plate and shell are removed together from the dump box and heated for about 2 minutes at about 450°F. The shell is then stripped from the pattern plate with the aid of the ejector pins which are an integral part of the pattern plate. The tops of these pins, at the pattern-plate surface, move upward simultaneously, lifting the shell mold from the pattern plate. Two mating shells, produced as described above, are securely fastened together to form a complete mold. Shell molds may be poured either with the parting surface vertical (standing on edge) or with the parting surface horizontal as with ordinary sand molds.

To produce shell cores, the sand/resin mixture is poured, or blown under low pressures, into the interior of a heated metal core box. After a sufficient period of time, the loose mix is poured out, leaving a shell adhering to the heated core-box surfaces. After heating for the additional curing, the shell core is removed from the core box.

The advantages of shell molding include smooth surfaces (in the range of 125 micro-inches, rms) and close tolerances (±0.003 inch per inch are obtainable). Dimensions which cross a parting line can be held to within ±0.010 inch per inch. The process is adaptable for mechanization, and several shell-mold and shell-core machines are commercially available. Less skill is required of machine operators than for sand casting molds. Permeabilities of shells are high, compared with other types of molds. Less sand is used compared with sand molding, and it is feasible in larger plants to recover the silica sand from the used shells. Shell molds may be made in advance and stored indefinitely. Practically all metals including the high-temperature alloy steels can be cast in shell molds.

The higher cost of the pattern manufacturing equipment limits the use of shell molding to sufficiently large production volumes to pay for pattern production out of manufacturing savings. The patterns must be considerably smoother and more accurate than the castings to be produced. Resin costs are also comparatively high, increasing the over-all process cost. Some casting shapes are not suited for the shell molding process, because a suitable parting and gating cannot be obtained. The size of the castings which can be cast in shell molds is limited by the maximum shell size that can be feasibly produced and poured.

Carbon Dioxide Process(2)

The carbon dioxide process involves the use of sand plus 1.5 to 6 percent liquid silicate as a binder. The mixture is packed around the pattern as in shell molding, but instead of being hardened by the application of heat to the thermosetting resin used in shell molding, carbon dioxide is blown through the sand/silicate mixture, thereby causing it to harden and to be gas permeable.

Plaster Molding(2,3)

In plaster molding, the mold material is a mixture of plaster of paris or gypsum and such fillers as talc, asbestos and silica flour. The fillers improve the mold strength and control the setting time of the plaster. The mold ingredients are mixed with water and poured over the pattern which is usually situated inside of a container, or flask, that confines the flow of the liquid plaster. After the plaster sets, the pattern is removed and the mold is dried at 400°F. Plaster molds produce castings having high surface finish and dimensional accuracy, plus faithful reproduction of fine detail and thin sections. However, because plaster is not a high-temperature refractory, its use in casting is limited to low-melting-point nonferrous metals such as aluminum, magnesium, and some copper-base alloys.

Permanent-Mold Casting(4,5)

Another method giving smoother surface finish and closer tolerances than sand casting is permanent-mold casting, a method which is also amenable to higher production rates than sand casting. The mold material is cast iron, steel, or bronze. Semi-permanent-mold materials include aluminum, silicon carbide and graphite. The mold itself is a casting which, after its halves have been cast over the pattern, is machined to the desired dimensions. Machining, in addition to producing the gating system in the mold halves, gives a good surface finish and improves the dimensional accuracy of the casting. To increase mold life and to make ejection of the casting easier, the surface of the mold cavity is usually coated with carbon soot or a refractory slurry, both of which also serve as heat barriers and control the rate of cooling of the casting.

Permanent mold casting is particularly suitable for the high-volume production of small, simple castings having fairly uniform wall thickness and no undercuts or intricate internal coring. The process can also be used to produce moderately complex castings though production volumes should be high enough to justify mold cost.

Permanent mold casting has these limitations: (a) although no maximum size has been established, the process is most applicable to small castings; (b) not all alloys are suited to permanent mold casting (e.g., high-melting-point alloys cannot be cast); (c) the process can be prohibitively expensive for low production; and (d) some shapes cannot be made because of the location of the parting line or difficulty in removing the casting from the mold. Limitations (b) and (d) offer no hindrance in investment casting.

Metals that can be cast in permanent molds include aluminum, magnesium, zinc and copper alloys, and hypereutectic gray iron. The metal being cast must have a melting point that is less than that of the mold material.

Aluminum alloys have a low density, which, combined with their oxide-film-forming characteristics, makes them flow somewhat sluggishly. The shrinkage of aluminum alloys during solidification is relatively large, and allowances must be made for metal feed during solidification. After solidification, the aluminum alloys are soft at elevated temperature, and castings can be distorted during removal from the mold.

Magnesium alloys are less applicable to permanent mold casting than aluminum alloys, and have relatively poor feeding characteristics in thin sections. Also, magnesium castings are more sensitive to hot shortness (brittleness at elevated temperature) than aluminum alloy castings. Generous fillets are required when the casting contains large bosses or when one section of the casting is much larger than another. Sharp detail cannot be obtained with magnesium alloy castings, and shapes that shrink onto mold sections are susceptible to cracking.

Copper alloys solidify at high temperatures, and some have narrow solidification ranges. They shrink onto cores and other mold elements and must be rapidly ejected from the mold.

Zinc alloys can be cast in permanent molds, but because zinc castings are usually made in large quantities, they are more often die cast.

Gray iron is used successfully in the high-volume production of small (1 oz. to 30 lb.), simple castings. However, more complex gray iron castings, with internal coring and marked changes in section, have also been successfully made by the permanent mold process.

Practical sizes of permanent mold castings are limited by cost. The maximum sizes that have been cast differ among the casting alloys. In high production, permanent mold castings weighing up to 30 lb. can be made from aluminum alloys in casting machines. However, much larger castings have been produced; for instance, aluminum alloy castings of relatively simple design with a trimmed weight of 780 lb. were produced in a three-section permanent mold. The mold, of gray iron, had outside dimensions of 9 by 9 ft. and weighed 25 tons. The castings with gates and risers weighed 1100 lb. each. Pouring time for each casting was 12 minutes. After pouring, castings were held in the mold for 20 minutes before ejection.

Magnesium alloys, despite their relatively low castability, have been cast in permanent or semipermanent molds to produce relatively large, complex castings. In one instance, a 17.7 pound magnesium casting was poured in a semipermanent mold. The mold utilized vertical parting and an oil-sand core to develop vanes and internal surfaces in the casting. Surface finish of the casting varied from about 250 to 500 microinches. In another instance, 53-pound castings, 30 inches in diameter, were cast in a two-segment permanent mold with vertical parting. These castings were used as ends for fiber rolls, which have a heavy hub section and a thin peripheral rim and function like spools for thread.

Saddle tanks, which function as 300-gal auxiliary fuel tanks and are components of an aircraft wing structure, were successful cast in a magnesium alloy in a two-segment, vertically-parted semipermanent mold using 42 expendable cores. The trimmed castings each weighed 30 pounds, and measured 1 by 4 feet. Wall thickness ranged from 5/16 to 5/8 inch.

The dimensional accuracy of permanent mold castings is affected by short-term and long-term variables. Short-term variables are those that prevail regardless of the length of run:

1. Cycle-to-cycle variation in mold closure or in the position of other moving elements of the mold
2. Variations in mold closure caused by foreign material on mold faces or by distortion of the mold elements
3. Variations in thickness of mold coating
4. Variations in temperature distribution in the mold.

Long-term variables that occur over the life of the mold are caused by:

1. Gradual and progressive mold distortion resulting from stress relief, growth and creep
2. Progressive wear of mold surfaces, caused mainly by cleaning procedures.

Dimensional variations can be minimized by keeping rates of heating and cooling at constant levels, operating on a fixed cycle and maintaining clean parting faces. It is particularly important to select mold-cleaning procedures that remove a minimum of mold material.

Mold thickness and the design of supporting ribs have an effect on the warpage of the mold at operating temperatures. Supporting ribs on the back of a thick mold can warp the mold face in a concave way. The design error can alter casting dimensions across the parting line as much as 1/16 inch. Adequate mold lock-up can contribute to the control of otherwise severe warpage problems.

Mold erosion resulting from metal impingement and cavitation due to improper gating design contribute to heat checking and rapid weakening of the mold metal; this can contribute to rapid dimensional variation during a long run.

Mechanical abrasion due to insufficient draft or to improperly designed ejection systems also contributes to the rapid variation of casting dimensions.

Sliding mold segments require clearance of up to 0.015 in. to function under varying mold temperature. The clearance and other mechanical problems associated with sliding mold segments contribute to variation in casting dimensions. Sand cores further aggravate the problem.

Surface finish on permanent mold castings depends mainly on:

1. Surface of the mold cavities - Surface of the castings can be no better than that of the mold cavities; heat checks and other imperfections can be reproduced on the casting surface.
2. Mold coating - Excessively thick coatings, uneven coatings, or flaked coatings degrade casting finish.
3. Mold design - Enough draft must be provided to prevent galling or cracking of casting surfaces; the location of the parting line can also influence the surface finish of the casting. Gating design and size have a marked effect on casting finish, because they influence the rate and smoothness of flow on the poured metal.
4. Venting - The removal of air entrapped in mold cavities is important to insure smooth and complete fill.
5. Mold temperature - For optimum casting surface finish, mold temperatures must be appropriate for the job and must be reasonably uniform.
6. Casting design - Severe changes of section, complexity, requirements for change in direction of metal flow, and large flat areas all adversely affect surface finish.

Defects that can occur in permanent mold castings are porosity, dross, non-metallic inclusions, misruns, cold shuts, distortion and cracking.

Manually operated equipment is generally more economical for low production quantities, but for medium to high production quantities machine molding invariably costs less.

Die Casting(5,6)

Die castings are produced by forcing molten metal under pressure into metal molds called dies.

As a casting process it is closely related to permanent mold casting in that in both processes reusable metal molds are used. The two processes differ in mold-filling method; whereas in permanent mold casting mold filling depends on the force of gravity, die casting involves metal injection under high pressure (up to 100,000 psi) and high velocity. Because of this high-velocity filling, die casting can produce shapes that are more complex than those produced by permanent mold casting. (In Europe, die castings are generally called "pressure die castings", and the term "gravity die casting" is equivalent to permanent mold casting.)

In die casting, after the die has been closed and locked, molten metal is delivered to a pump, which may be either cold (cold-chamber die casting) or heated to the temperature of the molten metal (hot chamber). The pump plunger is advanced to drive the metal quickly through the feeding system while the air in the die escapes through vents. Sufficient metal is introduced to overflow the die cavities, fill overflow wells and develop some flash. As the cast metal solidifies, pressure is maintained through a specified time while the casting solidifies and shrinks. The die is then opened and the casting ejected. While the die is open, it is cleaned and lubricated as needed, then it is closed and locked, and the cycle repeated.

The advantages of the die casting are:

1. More complex shapes can be made by die casting than by permanent mold casting.
2. Because the dies are filled by pressure, castings with thinner walls and greater dimensional accuracy can be produced than by almost any other casting processes except investment casting.

3. Production rates are higher in die casting, especially when multiple-cavity dies are used, than in other casting processes.

4. Because die castings are produced by almost completely finished parts, the investment in inventory and factory floor space is reduced to a minimum.

5. Dies for die casting (as with molds for permanent mold casting) can produce many thousands of castings without significant change in casting dimensions.

6. Metal cost is often lower than in other casting processes, because die casting permits casting of thinner sections.

7. Many die castings can be plated (finished) with minimum surface preparation.

8. Some aluminum alloy die castings can develop higher strength than comparable sand castings.

9. Labor costs per unit of production are lower than in permanent mold casting.

The principal limitations of die casting are:

1. Casting size is limited; casting weight seldom exceeds 50 lb. and normally is less than 10 lb.

2. Depending on casting contours and gating, difficulty may be encountered with air entrapped in the die; entrapped air is a principal cause of porosity.

3. The facilities, consisting of the machine, the auxiliary equipment, and the dies, are relatively expensive; because die castings are small, large quantities of castings are required for the process to be economical.

4. With few exceptions, commercial use of the process is limited to metals having melting temperatures no higher than those of copper-base alloys.

Depending on degree of mechanization, process variables, and the part being cast, hot-chamber machines generally operate at rates of 50 to 500 shots per hour. Special machines greatly exceed these rates, ranging from 2000 to 5000 shots per hour up to 18,000 shots per hour for a zipper-casting machine.

Slides are the movable die parts needed to build up die surfaces; they are used when it is impossible to avoid undercuts in a casting. The part of the die-cavity wall that forms the undercut portion is made on the face of a slide accurately fitted in a guide cut in the die block. The slide must be retracted before the casting can be ejected. A separate locking mechanism must be provided for each slide. The use of the slides adds considerably to die cost.

The rate of die wear is influenced chiefly by the temperature of the casting metal and by the design of the die. When the metal has a casting temperature no higher than that of zinc alloys, and the die is of simple design, it is possible to obtain more than 500,000 shots before there is significant die wear. As metals with higher casting temperatures are used, progressing from zinc to aluminum and thence to copper alloys, die wear increases rapidly, regardless of die design. As the configuration of the casting and gating system becomes more complex, wear in localized portions of the die also increases.

A good die casting has a uniform surface free of surface imperfections due to uncontrolled flow of metal (imperfections such as heat-sink marks, pits, porosity, swirls, cold shuts and misruns), and it exhibits no imperfections caused by oil deposits and dross inclusions. A normal amount of buffing seldom removes surface flaws. Excessive buffing can break through the dense skin and expose underlying porosity.

Hardware finish is a term describing a die-casting surface finish that will accept decorative plating. To obtain good hardware finish, dies must be properly gated, overflow patterns must be correctly placed to remove trapped gas and create heat balance, venting must be ample, and only a minimum of die lubricant must be used. Polishing of the die cavities will greatly increase the number of shots that can be made with one lubrication. The location of water lines for cooling the die is important; improper cooling can create either hot spots that produce sink marks in the surface of the casting or cold spots that cause metal to freeze prematurely. If openings from the die cavity into overflows are too large, the casting metal will circulate in and out of the overflows and produce swirls, which appear in the casting surface and remain after plating.

Factors influencing the cost of die castings, and the direction of their influence, are:

1. Quantity - Unit cost decreases as the quantity increases, because with a large production run fixed costs and tooling costs can be spread over a large number of castings, and more-efficient tooling can be provided.
2. Tooling - The more mold cavities in the die, the lower the unit cost of each casting, because more castings can be produced per unit of time; for large production runs, it may be economical to use a more complex die design and to reduce the number of secondary operations.
3. Casting design - The more complex the casting, the higher are the costs of cores and slides, removal of flash and gates, and die maintenance.
4. Section thickness - Exceptionally thick or thin sections result in higher-than-normal rejection rates.
5. Dimensional tolerance and surface finish - Unusually close tolerances and surface-finish requirements contribute to higher initial tooling and tool-maintenance costs, and may slow production rates.
6. Cost of the casting metal - In addition to having a direct influence on over-all cost, the type of casting metal used also affects tooling cost.

Processes that are competitive with die casting usually are other casting processes. In some applications, machining, cold heading and welding may be as economical as die casting, particularly when end use is noncritical or when production quantity is small. Since die casting is a high-production process, the quantity of reproductions to be made is often the deciding factor as to which process is best.

Centrifugal Casting(3,5)

In centrifugal casting the inertial forces of rotation distribute the molten metal into the mold cavities in such a way as to produce high-density castings with low gas or air entrainment. There are essentially three types of centrifugal casting: true centrifugal casting, semicentrifugal casting, and centrifuging. The first two processes produce hollow cylindrical shapes and parts having axial symmetry. In the third process, the mold cavities are located at the ends of radially-located gates that feed the poured metal into a centrally-located pouring basin and sprue. In true centrifugal casting, us[illegible]r making cast iron and steel pipes and similarily shaped objects, the mold material is sand, backed by a metal pipe called a flask which, with the sand it contains, is rotated while the molten metal is introduced at one end of the flask. The other centrifugal casting processes may employ permanent molds (or dies) made of forged steel or cast iron lined with graphite to facilitate casting removal. Rotational speeds are chosen to produce accelerations of between 40 and 60 gravities. In the semicentrifugal and centrifuging processes, the melting points of the materials to be cast are limited by the strength and temperature capabilities of the die material.

Powder Metallurgy (P/M)(1,7)

Powder Metallurgy (P/M) is a material processing technique used to consolidate particulate matter, both metals and/or nonmetals, into discrete shapes. P/M methods also apply, with little modification, to ceramics and other types of nonmetallic materials. Complex composites of both metallic and nonmetallic phases are being fabricated by (P/M) methods in increasing quantities to provide the material properties required in the aerospace, electronic and nuclear energy industries.

P/M products are usually finished parts such as gears or cams. The technique employed consists essentially of subjecting the metal powders to pressure and heat. The heat treatment, called sintering, is performed at some temperature below the fusion point of the main constituents of the products. Instead of pure metal powders, alloy powders may be used singly or as mixtures. Also, metal powders may be used in mixtures with metallic or nonmetallic components. Powder metallurgy thus permits the production of metallic, or metal-like, bodies of many shapes without the use of standard metal-forming techniques such as melting and casting.

Many refractory metals have such high melting points that conventional melting and casting is difficult, if not impossible. Powder metallurgy is the ideal method, for example, of producing tungsten filaments. Metal combinations in which the characteristics of each constituent are retained are of particular interest for certain electrical applications, and they can be produced by P/M methods. For instance, heavy-duty electrical contacts and welding electrodes combine a skeleton of refractory metal, highly resistant to abrasion and arcing, with a second metal of low melting point and high conductivity. Alloying between the constituents is negligible so that the original properties of the individual metals are preserved.

Other examples are cemented-carbide high-speed cutting tools, cermets, and dispersion alloys. Cermets are predominantly nonmetallic, or ceramic, with a metallic binder phase. Dispersion alloys contain minute nonmetallic particles dispersed in a metallic matrix. Cermets are important as nuclear reactor components, such as fuel elements which consist of combinations of uranium oxide and binder metals, and control or moderator elements which contain fine dispersions of boron and other neutron-capturing elements in aluminum, stainless steel, or zirconium matrices.

The largest application of P/M is in the production of small metal parts, gears, cams, and other components for machines and instruments requiring closely controlled dimensions and properties. These parts can often be produced at lower cost by powder metallurgy than by other metal-forming methods. The parts may be steel, brass, or alloys of iron with copper, nickel, or chromium.

The development of metallic bodies of closely controlled porosity has made possible so-called self-lubricating bronze and iron-base bearings which can be impregnated with oil and used in places inaccessible to external lubrication. Porous metal is also used effectively in oil-pump gears, metal filters, and diaphragms.

Current-collector brushes in electrical machinery are laminated P/M products. Copper-lead bearings whose constituents are not miscible in the liquid or solid state are typical of metal powder alloys of unusual components.

After sintering the part may be ready for use or secondary operations such as repressing, resintering, infiltration with a molten metal or impregnation with plastic or liquid lubricant, or a combination of these may be performed to achieve specific properties. More conventional operations such as machining, tumbling, plating and heat treatment may also be carried out. A number of applications require joining operations; brazing, soldering, or welding of these parts onto other metal bases is common practice in the hard metal and refractory metal industries. Finishing and joining operations must frequently be adapted to the specific properties of P/M products: care must be taken in machining because of the porosity, plating methods must be adjusted to prevent corrosion caused by the porosity; special fluxes or inert or reducing gaseous media must be used to prevent excessive oxidation during brazing and welding. Two very important factors should be noted: (1) the process offers the greatest economic advantages when very few, if any secondary operations are necessary, and large quantities of a part may be mass produced at rapid rates; and (2) the process variables may be adjusted to produce parts with controllable types and amounts of useful porosity or with densities approaching the theoretical value that was analogous to and competitive with conventional cast and wrought materials, including forgings. Additionally, many alloys and complex multiphase materials can be economically manufactured only by P/M techniques.

A comparison of P/M with the more conventional metal forming methods reveals the advantages and limitations.

Powder metallurgy does not make up a preponderant segment of the metallurgical industries. In spite of the accelerated growth of its different branches, P/M has remained a limited and specialized field. The reasons for this are both economic and technical. Powdered starting materials, with the exception of most iron powders, are more expensive than other raw materials. Tools and dies must be durable, and usually return their cost only when many thousands of the same part are produced. Special tools are required for the forming of complex shapes because the powder does not flow readily into lateral protrusions. Powders of high specific volume require long compression strokes, which in turn impose slow production rates. Also, the large surfaces of the powders are prone to gas adsorption, leading to brittleness of the end product.

Beryllium products are made exclusively of P/M and in the electronics, nuclear, and rocket fields, P/M dispersion alloys, refractory metals, and cermets with unusual properties are being developed. High-density forging preforms from powders of titanium alloys, nickel-chromium heat-resistant alloys, and high alloy and tool steel are also new developments in P/M, which offers economic advantages due to reduced machining time and scrap as well as to potentially superior properties that can be obtained because of grain size control and tailor-made special compositions.

The increasing use of large P/M parts for structural applications by the automobile industry represents a very important contemporary development. At the outset all P/M parts were small, less than a few square inches in cross section, and the mechanical properties were considered barely comparable to more conventional materials. Today the size has increased many times and large parts of a foot or more in diameter and weighing ten to fifty pounds are being produced in large quantities. Materials with mechanical properties far exceeding those of more conventional materials have been developed by using new alloying elements for iron-base materials, by improving heat treatments, by using improved powders and by achieving higher densities. Not only can high strengths be obtained but also high levels of ductility and toughness in P/M parts are available. The notion that P/M parts are brittle and fragile is completely invalid today.

The disadvantages of P/M center on tooling costs and on the toxicities and flammabilities of the metal powders. Handling of certain fine powders can present severe health hazards. Pyrophoricity (spontaneous ignition or oxidation) is a potential danger for many metals, including the more common types when they are in a finely divided form with large surface-area-to-volume ratios. Toxicity of powders is normally related to inhalation or ingestion, the basic cause of which is not merely the property of the material but the ability of small particles to remain suspended in air and resist collection and removal. A 100-micron particle will settle at a rate of about 60 ft/min; a 50-micron particle at a rate of about 10 ft/min; and a 10-micron particle at about 0.5 ft/min. In normal situations air has a turbulent velocity of about 35 ft/min. Consequently, particles in the 50-micron range float easily for extended periods in the air stream.

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APPENDIX B

Glossary of Waxes, Resins, and Chemicals Associated with Investment Casting Waxes*

Acetal Resin - Also called polyacetal. A polyoxymethylene thermoplastic polymer obtained by anionic polymerization of formaldehyde; hard, rigid, strong, tough and resilient; specific gravity 1.425; nontoxic, even when thermally decomposed.

Acrylic Resin - A thermoplastic polymer or copolymer of acrylic acid, methacrylic acid, esters of these acids, or acrylonitrile; they can be converted to thermosetting resins by adding acrylic anhydride, acrylamide, or glycol esters or acrylic acid.

Adipic Acid - An organic-acid casting wax filler material; white crystalline solid; melting point 152°C; boiling point 265°C; specific gravity 1.360; low toxicity; used also in manufacture of nylon and polyurethane foams, is also a food additive.

Balsam - A resinous mixture of varying composition obtained from several species of evergreen trees or shrubs. Contains oleoresins, terpenes, and usually cinnamic and benzoic acids. All types are soluble in organic liquids and insoluble in water. They are combustible and in general non-toxic. A component of investment casting waxes.

Carnauba Wax - Also known as Brazil wax, it is a vegetable wax and is the hardest and most expensive commercial wax. Hard, amorphous, light yellow to greenish brown with a specific gravity of 0.995 (at 15°C) and a melting point of 84 to 86°C, it is soluble in ether and boiling alcohol and alkalies, but not in water. It is combustible and nontoxic. Its uses are in shoe polish, leather finishes, waterproofing, and confectionary, among others.

Cellulosic Plastics - A group of semisynthetic thermoplastic polymers based on cellulose; examples are cellulose acetate, cellulose nitrate (nitrocellulose), carboxymethi-cellulose, and ethylcellulose, the latter being at least one member of this group that has been used as a component in investment casting waxes.

Coal-Tar Resin - See Coumarone-Indene Resin

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*The bulk of the terms defined and/or discussed in this glossary were taken from patents and trade association publications. Definitions and other information came from the sources listed in the bibliography at the end of this Appendix.

Component - A casting wax component is an ingredient, and is usually either a resin or a wax and can be of either natural or synthetic origin. (See Filler)

Congo Resin - A possible casting wax component. A variety of copal fossil resins, the natural product is insoluble in organic solvents, but when thermally processed (cracked) it is soluble in all organic solvents, fatty acids, and vegetable oils.

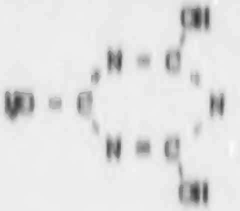
Copal - A group of fossil resins used to some extent in varnishes and lacquers. Insoluble in oils and water. Most important types are congo, kauri and manila.

Coumarone - Benzofuran; A bicyclic ring compound derived from coal-tar naphtha.

Coumarone-Indene Resin - A thermosetting resin derived by heating a mixture of coumarone and indene with sulfuric acid, which induces polymerization. At room temperature it is soft and sticky; on heating it hardens to a resinous solid.

Cumar Resin - Cumar is a trademark for a series of neutral, stable, synthetic resins of the coumarone-indene type, manufactured from selected distillates or tar. It is used as a softener and tackifier in varnishes, floor tile, rubber products, printing ink, adhesives, and water-proofing materials.

Cyanuric Acid =



Cyanuric acid has been used as a filler in the past but is not presently used because of its relatively high price (about 80¢/lb). It is odorless, and decomposes to cyanic acid (HOCN) at 320 to 350°C before melting. Cyanuric acid is soluble in water and hot mineral acids, and is insoluble in alcohol and acetone. Its specific gravity is 1.768. Both cyanuric acid and cyanic acid are highly toxic by ingestion or inhalation. Despite this fact, one industry source stated that cyanuric acid is safe for wax filling applications as it "does not evolve toxic gases in the temperature range used in casting operations." Cyanic acid is a severe explosion risk, and cyanuric acid vapors are also quite flammable.

N,N' Ethylene Bis Stearimide - At least one manufacturer used this material in production of filled waxes. No information is available on the chemical or toxicological properties.

Dammar - A group of tree-derived resins soluble in hydrocarbon and chlorinated solvents; partially soluble in alcohol; insoluble in water.

Epoxy Resin - A thermosetting resin having potential application as an investment casting wax filler; very low toxicity in cured state, but emits highly toxic fumes when heated to decomposition. Not currently used in waxes. Expensive.

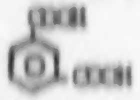
Filler - A casting wax filler is usually an organic material that melts at a significantly higher temperature than the wax; its functions are mainly to reduce the cooling and solidification shrinkage of the wax and to increase the heat transfer rate of the wax; fillers should be able to burn without leaving ash or residue, and the products of decomposition should be nontoxic. (See Component)

Fischer-Tropsch Wax - A wax made by the catalytic process known as the Fischer-Tropsch process in which water gas or other synthetic gas mixtures containing carbon monoxide are reacted with hydrogen to produce aliphatic straight-chain hydrocarbons and oxygenated derivatives.

Fumaric Acid - An organic-acid casting wax filler material; colorless crystalline solid; specific gravity 1.635; melting point 287°C; low toxicity; used also as modifier for polyester, alkyd, and phenolic resins, and as a food additive.

Indene - A component of crude coal-tar distillates.

Ionomer Resin - A thermoplastic crosslinked copolymer of ethylene and a vinyl monomer with an acid group such as methacrylic acid. Cannot be completely dissolved in any commercial solvent.

Isophthalic Acid - 

Isophthalic acid is one of the most widely used wax fillers in the investment casting industry. It is combustible, and has a melting point of

345 to 348°C; it also sublimes. Isophthalic acid is slightly soluble in water; is soluble in alcohol and acetic acid, and insoluble in benzene and petroleum ether. Acute local toxicity by ingestion, inhalation, or skin contact is slight. The LD_{50} of isophthalic acid by interperitoneal injection in mice is 4,200 mg/kg. The acute systemic and chronic toxicology of isophthalic acid is not known.

Kauri - See Copal

Mastic - A resinous exudation of a tree found in the Mediterranean area; used in chewing gum, varnishes, and to some extent in adhesives and dentistry.

Microcrystalline Wax - A wax, usually consisting of branched chain paraffins and characterized by a crystal structure much smaller than normal wax and by higher viscosity than normal wax. It is obtained by dewaxing tank bottoms, refiner residues and other petroleum waste products. Average molecular weight is about twice that of ordinary paraffin; that is, about 500 to 800. Uses include: adhesives, paper coating, cosmetic creams, floor wax, electrical insulation, glass fabric impregnation, leather treatment and emulsions. Two naturally occurring microcrystalline waxes are chlorophyll and beeswax, of which the latter still finds some use in investment casting.

Montan Wax - Also called lignite wax; melting point 80° to 90°C; a hard white wax; soluble in carbon tetrachloride, benzene, and chloroform, insoluble in water. Derived from lignite. Substitute for carnauba and beeswax. Montanic.

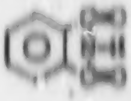
Nylon - Used as a filler in waxes; not likely currently used; contains nitrogen, which can evolve cyanide or nitrogen oxides at high temperatures.

Paraffin Wax - A white translucent, tasteless, odorless solid consisting of a mixture of solid hydrocarbons of high molecular weight (e.g., $C_{36}H_{74}$). Paraffin waxes are soluble in benzene, warm alcohol, chloroform, turpentine, carbon disulfide, and olive oil; insoluble in water and acids. Specific gravity is 0.880 to 0.915; melting point range is 47 to 65°C generally, though a narrow melting range of only 2 or 3 degrees is more desirable in paraffin waxes used in investment casting.

Pentaerythritol $C(CH_2OH)_4$ - Although a patent exists for the use of polyhydric alcohols as a wax filler, pentaerythritol is apparently the only member of this group to be used on a commercial scale. Pentaerythritol melts at 262°C and boils at 276°C. It is soluble in water; slightly soluble in alcohol; and insoluble in benzene, carbon tetrachloride, ether, and petroleum ether. The specific gravity of pentaerythritol is 1.399 (at 25°C). It is combustible and is a moderate fire hazard. Its toxicity is unknown. The toxicity of pentaerythritol derivatives listed in the Registry of Toxic Effects of Chemical Substances by oral application in rats ranges widely, with LD_{50} of diphenyl phosphite tetra pentaerythritol at 1.5 mg/kg and LD_{50} of pentaerythritol triacrylate at 2460 mg/kg.

Phenolic Resin - Any of several types of synthetic thermosetting resin obtained by the condensation of phenol or substituted phenols with aldehydes such as formaldehyde, acetaldehyde, and furfural. Phenol-formaldehyde resins are typical and constitute the chief class of phenolics.

Phthalimide -



Phthalimide is structurally similar to isophthalic acid, and exhibits some similar properties. Its melting point is 233 to 238°C; it also sublimes. Like isophthalic acid, it is combustible and is slightly soluble in water and insoluble in cold benzene; it is slightly soluble in ether and is soluble in aqueous alkalies and boiling benzene. Phthalimide may emit toxic fumes when heated; hydrogen cyanide or nitrogen oxides may be produced by phthalimide-containing waxes during wax burnout, depending on the temperatures and oxygen concentration in the furnace. Cyanide fumes would not be expected from a properly operating furnace. Little is known about the toxicity of phthalimide.

Polycarbonate - A synthetic thermoplastic resin derived from bisphenol A and phosgene; a linear polyester of carbonic acid; nontoxic; combustible but self-extinguishing.

Polyester Resin - Any of a group of thermosetting synthetic resins, which are polycondensation products of dicarboxylic acids with dihydroxy alcohols. They are a special class of alkyd resin, but, unlike other types, are not usually modified with fatty acids or drying oils. Their outstanding characteristic is their ability, when catalyzed, to harden at room temperature under little or no pressure.

Polyethylene $(C_2H_4)_n$ - Polyethylene is widely used as a casting wax component. Its molecular weight varies depending on the degree of polymerization. It is a thermosetting white resinous solid, highly resistant to temperature and chemical stresses. It is insoluble in organic solvents, and does not stress-crack. Polyethylene is combustible. Although polyethylene is non-toxic, apparently little research has been done on this ubiquitous substance. It is an unintentional food additive, resulting from contact of food with polyethylene packaging materials. Toxicity studies in which polyethlene was surgically impanted in mice and rats yielded contrasting results. Tumors were produced in mice by a dosage as low as 330 mg/kg but the lowest dosage causing this effect in rats was 2,120 mg/kg.

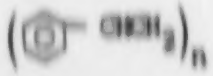
Polyhydric Alcohols - Polyhydric alcohols are alcohols containing three or more hydroxyl groups. Those having three OH groups (trihydric) are glycerols; those with more than three are called sugar alcohols. In investment casting, the preferred polyhydric alcohol is pentaerythritol, which is a polyhydric alcohol of tetra substituted methane having alcohol groups of up to and including six carbon atoms with OH groups on at least half of the carbon atoms.

Polyol - A polyhydric alcohol.

Polyolefin - A class or group for thermoplastic polymers derived from simple olefins; among the more important are polyethylene, polyporpylene, polybutenes, polyisoprene, and their co-polymers. This group comprises the largest tonnage of all thermoplastics produced. Polyethylene is used to some extent as a wax component; different molecular weights give different performances in wax.

Polypale Resin Ester - Proprietary trade name of a resin presently used by at least one wax manufacturer. Its chemical composition is unknown, as are its chemical and toxicological properties.

Polystyrene -



Polystyrene is possibly the most widely used filler in the industry. It is a thermoplastic synthetic resin with high strength and impact resistance. The molecular weight of polystyrene is variable depending on the degree of polymerization. It is an excellent electrical insulator. Polystyrene is attacked by hydrocarbon solvents, but is resistant to organic acids, alkalies, and alcohols. It is combustible and is not self-extinguishing. Polystyrene generally contains styrene monomer approximately as 0.1 percent of the total weight. Polystyrene is considered nontoxic, although surgical implantations of as low as 10 mg/kg have caused neoplastic effects (production of tumors) in rats.

Polyvinyl Chloride - A synthetic thermoplastic polymer; combustible but self-extinguishing; nontoxic, except when burned releases HCl fumes and phosgene and possibly unpolymerized vinyl chloride monomer which is toxic and has been linked to cancer of the liver.

Resin - Resins are classed as either natural or synthetic. Natural resins are vegetable derived; they are amorphous mixtures of carboxylic acids, essential oils and terpenes occurring as exudations on the bark of many varieties of trees and shrubs. They are combustible and electrically nonconductive. When cold they are hard and glassy with a conchoidal fracture; at higher temperatures they are soft and sticky. Rosin is a natural resin. Synthetic resins are high polymers resulting from a chemical reaction between two or more substances, usually with heat or catalyst. Examples are synthetic rubber, siloxanes, and silicones. (Water-soluble modified polymers often referred to as resins are not really synthetic resins.) Polystyrene is a thermoplastic synthetic resin used in investment casting. Plastics are resins, but with such additives as fillers, colorants and plasticizers. Polychlorinated terphenyl serves the function of a resin in investment casting waxes. The preferred resins in investment casting are polymers and copolymers of cyclic alkenes; for example, terpenes and naphthenes which solidify into a hard state such as occurs with rosins and the petroleum-base higher melting naphthenes. Typical higher thermoplastic resins used in pattern waxes include terpene phenolics, methyl ester of rosin, hydrogenated rosins, polymerized rosins, rosin derivatives, coal tar derivatives, petroleum derivatives, styrene derivatives, alkyds, polyesters, chlorinated polyphenyls, polyamides, coumarone-indene resin, and diphenyl bis stearamide.

A. Natural Resins
- rosin
- balsam
- kauri
- congo
- damar
- mastic
- copal
- sandarac
- shellac

B. Synthetic Resins
1. Thermoplastic resins
   - acetal (copolymer, homopolymer)
   - acrylic
   - cellulosic (e.g., acetate, nitrate, butyrate, propionate, ethylcellulose)
   - polycarbonate
   - polyolefin (polyethylene, polypropylene, polybutylene)
   - polystyrene
   - polyvinyl halide
2. Thermosetting resins
   - amino-aldehyde (melamine)
   - polyester (allyl, alkyd)
   - epoxy
   - ionomer
   - phenolic

Rosin - A natural resin, rosin derives from pine tree sap; gum rosin is the residue obtained after the distillation of turpentine oil from the oleoresin tapped from living trees; wood rosin is obtained by extracting pine stumps with naphtha and distilling off the volatile fraction. In general, rosin comes in angular, translucent, amber-colored fragments; specific gravity is about 1.08, melting point is between 100°C and 150°C. Though insoluble in water, it is freely soluble in alcohol, benzene, ether, glacial acetic acid and carbon disulfide. The toxicity of rosin is low. At room temperature, rosin is hard and friable; when warmed it becomes soft and sticky.

Sandarac - A natural resin obtained from Morocco. Its commercial form is yellow, brittle, amorphous lumps or powder; soluble in alcohol; insoluble in benzene and water.

Shellac - A natural resin secreted by the insect Laccifer lacca and deposited on the twigs of trees in India.

Styrene (monomer)

Styrene monomer is used to a limited basis by the investment-casting industry as a filler. Styrene has a melting point of -31°C and boiling point of 141°C. Its lower explosive limit is 1.1 percent; upper explosive limit is 6.1 percent. Flash point is 31°C and autoignition temperature is 490°C. Styrene is moderately toxic by inhalation, ingestion, or skin irritation. Inhalation of concentrations as low as 20 mg/m^3 have caused toxic glandular effects in humans and a concentration of 10,000 ppm over 30 minutes has been lethal to humans. Data on the toxicity of styrene by ingestion is not conclusive with LD_{50} for rats being 5,000 mg/kg^2 and LD_{50} for mice being 316 mg/kg^2. The U.S. Occupational Standard for styrene is that the time-weighted average concentration is not to exceed 100 ppm and peak concentration is not to exceed 600 ppm.

Terpene Polymer - A resinous synthetic thermoplastic material made by the polymerization of beta-pinene and dipentene (which are the monocyclic and dicyclic forms of terpene, which is itself an unsaturated hydrocarbon having the empirical formula $C_{10}H_{16}$). Terpene resin is used in paper coating, and hot-melt adhesive compounds. Two trade names are Nirez and Piccolyte.

Urea - Also known as carbamide, $CO(NH_2)_2$, a white crystalline powder; specific gravity 1.335; melting point 132.7°C; decomposes before boiling; soluble in water, alcohol, and benzene; has been used as a filler in investment casting waxes; synthesized from liquid ammonia and liquid carbon dioxide at high pressure; low toxicity except when heated, in which case with sufficient temperature and an oxidizing atmosphere nitrogen oxides are generated, and in a reducing atmosphere hydrogen cyanide can be generated.

Wax - A low-melting mixture or compound of high molecular weight, solid at room temperature and generally similar in composition to fats and oils, except that it contains no glycerides. Some are hydrocarbons; others are esters of fatty acids and alcohols. They are classed among the lipids; they are thermoplastic, but since they are not high polymers, they are not considered in the family of plastics. Waxes are classed as follows:

I. Natural
   a. Animal - beeswax, spermaceti, lanolin, shellac wax
   b. Vegetable - carnauba, candelilla, bayberry, sugarcane
   c. Mineral
      1. Fossil earth waxes - ozocerite, ceresin, montan
      2. Petroleum waxes - paraffin, microcrystalline, petrolatum

II. Synthetic
   a. Ethylenic polymers and polyol ether-esters - "Carbowax", sorbitol
   b. Chlorinated naphthalenes - "Halowax"
   c. Hydrocarbon type via Fischer-Tropsch synthesis

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APPENDIX C

INTERNATIONAL AGREEMENTS ON THE USE OF PCBs

C-1: DECISION OF THE COUNCIL OF THE ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (OECD), FEBRUARY 13, 1973

C-2: DIRECTIVE OF THE COUNCIL OF THE EUROPEAN ECONOMIC COMMUNITY (EEC), JULY 27, 1976

COUNCIL

DECISION OF THE COUNCIL

ON PROTECTION OF THE ENVIRONMENT BY CONTROL OF POLYCHLORINATED BIPHENYLS

(Adopted by the Council at its 315th Meeting
on 13th February, 1973)

The Council,

Having regard to Articles 5(a), 5(b) and 12(c) of the Convention on the Organisation for Economic Co-operation and Development of 14th December, 1960;

Having regard to the Recommendation of the Council of 26th May, 1972, on Guiding Principles concerning International Economic Aspects of Environmental Policies /C(72)128/;

Having regard to the Note by the Secretary-General of 7th February, 1973, concerning Proposals for Concerted Action with respect to Polychlorinated Biphenyls /C(73)1(2nd Revision)/;

Considering that the use of Polychlorinated Biphenyls (PCBs) should be controlled by international action in order to minimise their escape into the environment pending the realisation of the ultimate objective of eliminating entirely their escape into the environment;

On the proposal of the Environment Committee;

I. DECIDES:

1. Member countries shall ensure that in their respective territories, Polychlorinated Biphenyls (PCBs) shall not be used for industrial or commercial purposes, except in the following categories of use:

Dielectric fluids for transformers or large power factor correction capacitors;

Heat transfer fluids (other than in installations for processing of foods, drugs, feeds and veterinary products);

Hydraulic fluids in mining equipment;

Small capacitors (subject to the provisions of Section II.2 below);

and, as regards the foregoing categories, PCBs may be used only in those applications in which the requirements for non-inflammability outweigh the need for environmental protection and in which Member countries are satisfied that sufficient controls are exercised in order to minimise risk to the environment.

2. In pursuance of paragraph I.1 above, Member countries shall:

(a) control the manufacture, import and export of bulk PCBs;

(b) institute adequate arrangements for the recovery, regeneration, adequate incineration or other safe disposal of surplus and waste materials;

(c) institute a special, uniform labelling system for both bulk PCBs and PCB-containing manufactured products and

(d) establish safety specifications for containers and transport.

II. RECOMMENDS that Member countries in implementing the Decisions set forth in Section I above:

1. control and manufacture, import and export of PCB-containing products;

2. work towards the elimination of the use of PCBs in small capacitors;

3. give priority attention to the elimination of the following applications of PCBs:

(a) heat transfer fluids in the food, pharmaceuticals, feed and vetinary industries;

(b) plasticisers for paints, inks, copying paper, adhesives, sealants;

(c) hydraulic liquids (other than in mining) and lubricating oils;

(d) vacuum pump fluids and cutting oils;

(e) pesticides;

4. request firms to use, as PCB replacements, materials which are less hazardous to human health and the environment than the range of PCBs now in use.

III. DECIDES:

At the beginning of 1974, 1975 and 1976 within the framework of the Environment Committee, Member countries shall exchange information on the main statistical data concerning PCBs, notably on:

(1) amounts of PCBs, including:

amounts manufactured by PCB type,
amounts imported " " " and by country;
amounts exported " " " and by country;
amounts incinerated " " "
amounts consumed " " " and by use;

(2) PCB replacements supplied by manufacturers, including the following points:

identification,
total amounts for each chemical type and for each use,
known toxicity and environmental hazard of each chemical type;

(3) disposal of surplus PCBs by incineration (including evaluation of incinerator efficiency) or by other efficient means.

IV. NOTES the "Technical Note on Polychlorinated Biphenyls" contained in the Appendix to this Decision.

V. INVITES Member countries to report to the Organisation at the beginning of 1974, 1975 and 1976 on measures taken in application of this Decision.

VI. INSTRUCTS the Environment Committee to follow the implementation of this Decision, to report at regular intervals to the Council on the information exchanges provided for in Section III of this Decision and to make such proposals to further improve and strengthen the control of production and use of PCBs as may seem appropriate in the light of experience gained and the continued work of the Organisation in this field.

Technical Note on
Polychlorinated Biphenyls

INTRODUCTION

Polychlorinated biphenyls (PCBs) are a group of stable substances comprising theoretically more than 200 individual compounds, many of which are widely used particularly because of their dielectric properties and non-flammability. At present they are obtained through chlorination of diphenyl, resulting in mixtures that are characterised by their average content of chlorine. Due to the persistence and toxicity of some of these compounds(1), effects have been observed in the environment and accidents reported over the last few years, which have given rise to serious concern in Member countries. In view of this concern the Sector Group on Unintended Occurrence of Chemicals in the Environment has investigated, on a priority basis, the need for, and feasibility of, concerted action to control the use and emissions of PCBs. The results of this enquiry lead to the following conclusions:

(a) Because of unacceptable levels of PCBs found in the environment and because of a number of incidents involving human health, some countries have taken or are considering taking action to control the use of PCBs;

(b) There are (1972) only six companies in O.E.C.D. Member countries that manufacture PCBs; five of them have already taken steps to reduce production to the supply for a few approved uses;

(c) PCBs can be replaced except for some users where their dielectric properties and non-flammability are essential;

(d) The technology for destruction of PCBs exists;

(e) Because of the many applications of PCBs in the wide range of consumer products moving in international trade, the situation will almost certainly become complicated unless international agreement is reached on allowable uses;

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(1) As of the time of the preparation of this Note, limited research studies with certain selected PCB-compounds seem to indicate that some of these compounds could eventually safely be used for certain applications.

(f) A rough estimate(1) indicates that consumption of PCBs in O.E.C.D. countries is matched by production. Considering in addition that import of chemicals from non-O.E.C.D. to O.E.C.D. countries is still restricted to basic chemicals, import of bulk PCBs is unlikely. It is, therefore, reasonable to suggest that the major part of the problem of unintended occurrence of PCBs can be solved through concerted action between O.E.C.D. Member countries.

USES OF PCBs

The applications of PCBs fall mainly into two categories:

- uses in closed systems;
- dissipative uses.

CLOSED SYSTEMS

The use of PCBs in closed systems can be defined as applications from which the PCBs are recoverable. PCBs in transformers, capacitors, heat transfer systems, hydraulic equipment, and vacuum pumps are in principle recoverable, since during use, the PCBs are not generally dispersed into the environment.

It is, however, important to distinguish between closed system uses that are controllable in practice and those where control cannot be guaranteed either:

- because frequent replacement of relatively small quantities will lead to disposal rather than recovery, or
- because a large number of small units widely dispersed will make collection extremely difficult, or
- because accidental leakage will cause imminent danger to human health.

A truly controllable use may therefore be defined as an application where:

- the PCBs are contained in a sealed circuit in large, long-life units;
- the quantities involved are such that there is an incentive for regeneration.

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(1) Production in 1971 amounted to about 48,400 metric tons and consumption in the 13 countries that provided numerical information to about 35,300 tons.

Following what has been said above, the only truly controllable uses of PCBs are in dielectrics for transformers and for large capacitors for power factor correction. Preventing escape of PCBs from these applications is mainly a problem of engineering design and of collection and destruction of used liquids, or, in the case of capacitors, of removal and destruction of PCB-impregnated material. These uses also being essential for safety reasons, it would be unreasonable to suggest that they be discontinued at the present time.

In all other closed systems, recovery of PCBs, although theoretically possible, would not be practical. Such applications should, therefore, be discontinued, unless safety requirements prevent the use of substitute products:

(i) Heat transfer systems

There may be some installations where the risk of explosion or fire must be avoided at all cost, and the danger of some escape of PCBs therefore is of less importance. Because of the risk of leakage, which can never be totally guarded against, the use of PCBs as heat transfer media in the food, drugs and feed industries should, however, be prohibited.

(ii) Hydraulic equipment, Vacuum pumps

Although the quantities involved in the individual case are relatively small, they will, unless recovered, add significantly to the environmental burden of PCBs. Theoretically, used fluids could be recovered, but in view of the difficulty of establishing a system to collect small quantities from many users, these applications should be discontinued. Furthermore, PCBs are generally not essential in hydraulic and pumping fluids, with the possible exception of hydraulic equipment in underground mining.

(iii) Small capacitors

These are typical examples of an application of PCBs in sealed units that are almost completely non-recoverable. Considering, for example, the many domestic electrical appliances in which capacitors are used, the cost of recovery would probably be prohibitive. A warning label showing that the equipment must not be disposed of as ordinary waste has been suggested; it is however, not likely to be sufficient, unless manufacturers and retailers would accept return of appliances that are out of use. The problem of recovery remains unresolved at the present time, but it has to be noted that Japan has stopped the use of PCBs in the manufacture of small capacitors.

DISSIPATIVE USES

The dissipative uses are those where recovery of used PCBs is not possible, since they are not contained in closed systems but in direct contact with the environment:

(i) Lubricating and cutting oils

The conditions under which these oils are used are such that there is continuous emission of small quantities into the environment. These applications, not being essential, should be discontinued;

(ii) Pesticide Use

This use has fortunately been abandoned in most countries already; if not, it should be banned with immediate effect. Since all O.E.C.D. countries require registration of pesticides, such a measure can easily be taken under existing legislation;

(iii) Plasticizers

The most important category, by volume of dissipative use is in the field of plasticisers. They are or have been used in most countries in a wide variety of consumer products including paints, inks, copying paper, adhesives, sealants, plastic products, etc., many of which are traded internationally. The major applications seem to be in the printing and paint industries.

The Printing Industry: Because of the risk of contamination of paper, which after recycling may be used in food packaging, the use of PCBs in the printing industry should be banned. In view of the fact that printing inks can be produced without PCBs and that in any case the amount used probably represents a total value of only about $30,000 in O.E.C.D. countries, such a measure should not cause serious economic damage. Assuming that copying paper is usually provided by the copying machine manufacturers (relatively few and big companies), any economic effects should be small.

The Paint Industry poses a somewhat different problem. Over the last decade, production has increased by 3.5 per cent - 5 per cent annually and the trend is rising in the O.E.C.D. area.

The over 2,000 million dollar West European paint industry alone accounts for some 40 per cent of the world output. Production is assured by a few large and a great many small companies (United Kingdom = 480, Italy and France = 350 etc.). This picture suggests that an overall ban on PCBs in paints could have some economic consequences.

It appears, however, that where used (e.g. in stoving applications) PCBs constitute something like 5 - 10 per cent of the paint. Few details are available in respect of the amounts used in paints, but taking one example (France) where 250 tons were used (1971) in a paint industry that produced something like 700,000 tons of paint, presumably only 2500-5000 tons would contain PCBs. Considering in addition that small paint manufacturers are generally highly specialised, and that the manufacturing process would not have to undergo a major change to replace the use of PCBs, a ban on PCBs should not cause any serious disturbance. The use of PCBs in paints has, in fact, been discontinued in some countries already. Figures for production (8,654,200 tons in 1969) and consumption (8,517,500 tons) in O.E.C.D. countries again suggest that import of paints from non-O.E.C.D. producers may be of minor significance.

In practice, none of the products where PCBs have been used as plasticizers can be recovered. Unless the use is totally eliminated, there will be continuous emissions into the environment due to evaporation, insufficient incineration etc. Judging by the action already taken in several countries, substitutes can readily be found for the whole category of plasticiser use of PCBs, which should, therefore, be banned.

It follows from what has been said above that for adequate protection of health and environment, but also to avoid undue competition in international trade, agreement is necessary on allowed uses of PCBs. In order to ensure that home production is not substituted by import, control action by governments, through licencing or other means, is essential. Measures are further necessary to ensure collection of used material, safety in transport of raw PCBs, and assessment of substitute materials:

(a) A uniform labelling system, internationally recognisable, should be developed for use on containers of raw PCBs as well as on any equipment or product containing PCBs.

(b) Suppliers (i.e. manufacturers and importers) should further provide containers for the transport of PCB-containing liquids: such containers must meet the appropriate specifications that have been laid down to ensure safety in transport of dangerous chemicals.

(e) Development of substitutes that are less hazardous than persistent PCBs(1) should be encouraged, but in view of the fact that no system for pre-market control of new chemicals has been introduced, testing for environmental effects is so far entirely the responsibility of the manufacturers. Information on replacement products should, therefore, be collected and reviewed.

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(1) See footnote on page 10

APPENDIX C (C-2)

COUNCIL DIRECTIVE

of 27 July 1976

on the approximation of the laws, regulations and administrative provisions of the Member States relating to restrictions on the marketing and use of certain dangerous substances and preparations

(76/769/EEC)

THE COUNCIL OF THE EUROPEAN COMMUNITIES,

Having regard to the Treaty establishing the European Economic Community, and in particular Article 100 thereof,

Having regard to the proposal from the Commission,

Having regard to the opinion of the European Parliament (1),

Having regard to the opinion of the Economic and Social Committee (2),

Whereas any rules concerning the placing on the market of dangerous substances and preparations must aim at protecting the public, and particular persons using such substances and preparations;

Whereas they should contribute to the protection of the environment from all substances and preparations which have characteristics of ecotoxicity or which could pollute the environment;

Whereas they should also aim to restore, preserve and improve the quality of human life;

Whereas dangerous substances and preparations are governed by rules in the Member States; whereas these rules differ as to the conditions of their marketing and use; whereas these differences constitute an obstacle to trade and directly affect the establishment and functioning of the common market;

Whereas this obstacle should therefore be removed; whereas this entails approximating the laws governing the matter in the Member States;

Whereas provisions relating to certain dangerous substances and preparations have already been laid down in Community Directives; whereas it is still necessary to establish rules for other products, in particular for those in respect of which international organizations have decided on restrictions such as polychlorinated biphenyls (PCB), a decision restricting the production and use of which was adopted by the Council of the OECD on 13 February 1973; whereas such a measure is necessary to prevent the absorption of PCB by the human body and the resultant danger to human health;

Whereas detailed examinations have shown that polychlorinated terphenyls (PCT) entail risks similar to those presented by PCBs; whereas the marketing and use of such substances should also be restricted;

Whereas it will be necessary, moreover, periodically to review the whole problem with a view to moving gradually towards a complete ban on PCBs and PCTs;

Whereas the use of chloro-1-ethylene (monomer vinyl chloride) as an aerosol propellant involves dangers to human health and the use thereof should be prohibited,

HAS ADOPTED THIS DIRECTIVE:

Article 1

1. Without prejudice to the application of other relevant Community provisions, this Directive is concerned with restricting the marketing and use in the Member States of the Community, of the dangerous substances and preparations listed in the Annex.

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(1) OJ No C 60, 13. 3. 1975, p. 49.
(2) OJ No C 16, 23. 1. 1975, p. 22.

ANNEX

Designation of the substance, of the groups of substances or of the preparation	Conditions of restriction
1. — Polychlorinated biphenyls (PCB), except mono- and dichlorinated biphenyls, — Polychlorinated terphenyls (PCT), — Preparations with a PCB or PCT content higher than 0·1 % by weight.	May not be used except for the following categories: 1. closed-system electrical equipment: transformers, resistors and inductors; 2. large condensers (≥ 1 kg total weight); 3. small condensers (provided that the PCB has a maximum chlorine content of 43 % and does not contain more than 3·5 % of penta- and higher chlorinated biphenyls); Small condensers which do not fulfil the above requirements may still be marketed for one year from the date of entry into force of this Directive. This restriction does not apply to small condensers already in use; 4. heat-transmitting fluids in closed-circuit heat-transfer installations (except in installations for processing foodstuffs, feedingstuffs, pharmaceutical and veterinary products; however, if PCBs are used in the abovementioned installations at the time of notification of this Directive, they may continue to be used until 31 December 1979 at the latest); 5. hydraulic fluids utilized in: (a) underground mining equipment; (b) machinery servicing cells for the electrolytic production of aluminium, in use when this Directive is adopted, until 31 December 1979 at the latest; 6. primary and intermediate products for further processing into other products which are not prohibited under this Directive.
2. Chloro-1-ethylene (monomer vinyl chloride)	May not be used as aerosol propellant for any use whatsoever.

2. This Directive shall not apply to:

(a) the carriage of dangerous substances and preparations by rail, road, inland waterway, sea or air;

(b) dangerous substances and preparations exported to non-member countries;

(c) substances and preparations in transit and subject to customs inspection, provided that they undergo no processing.

3. For the purposes of this Directive:

(a) 'substances' means
chemical elements and their compounds as they occur in the natural state or as produced by industry;

(b) 'preparations' means
mixtures or solutions composed of two or more substances.

Article 2

Member States shall take all necessary measures to ensure that the dangerous substances and preparations listed in the Annex may only be placed on the market or used subject to the conditions specified therein. Such restrictions shall not apply to marketing or use for Research and Development or analysis purposes.

Article 3

1. Member States shall bring into force the provisions necessary to comply with this Directive within 18 months of its notification and shall forthwith inform the Commission thereof.

2. Member States shall communicate to the Commission the text of the provisions of national law which they adopt in the field covered by this Directive.

Article 4

This Directive is addressed to the Member States.

Done at Brussels, 27 July 1976.

For the Council

The President

M. van der STOEL